Basic Ground-Water Hydrology

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science for a changing world

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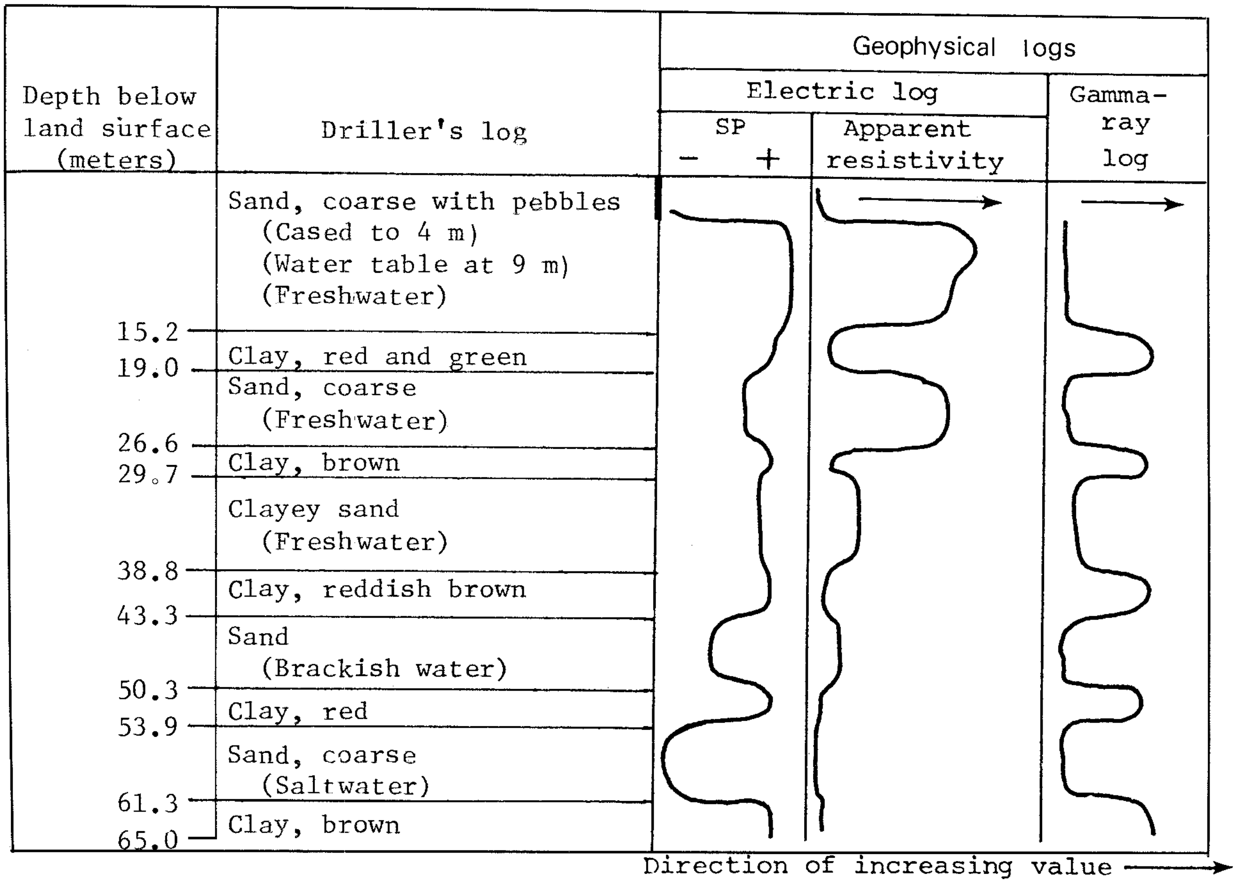
WELL LOGS



An important part of well construction is determining the character and the thickness of the different layers of material penetrated by the well and the quality of the water in the permeable zones. This information is essential for the installation of casing and for the proper placement of screens. Information on materials penetrated is recorded in the form of "logs." The logs most commonly prepared for supply wells are drillers' logs and geophysical (electric) logs. Copies of logs should be carefully preserved by the well owner as a part of the file on each well.

Drillers' logs consist of written descriptions of the material penetrated by wells. These descriptions are based both on samples of rock cuttings brought to the surface during drilling operations and on changes in the rate of penetration of the drill and in the vibration of the rig. The well driller may also collect samples of the rock cuttings for study by geologists on his staff or those on the staff of State geological surveys or Federal and State water-resources agencies. Descriptions of these samples made by utilizing a microscope and other aids are commonly referred to as a *geologic log* to differentiate them from the driller's log. If the well is to be finished with a screen, the well driller will retain samples of material from the principal water-bearing zones for use in selecting the slot size of screens.

Geophysical logs provide indirect information on the character of rock layers. The most common type of geophysical log, the type normally referred to as an *electric log*, consists of a record of the spontaneous electrical potentials generated in the borehole and the apparent electrical resistivity of the rock units. Several types of electric loggers are available, but nearly all provide continuous graphs of spontaneous potential and resistivity as a sensing device is lowered into and removed from the borehole. Electric logs can be made only in the uncased portion of drill holes. The part of the hole to be logged must also contain drilling mud or water.

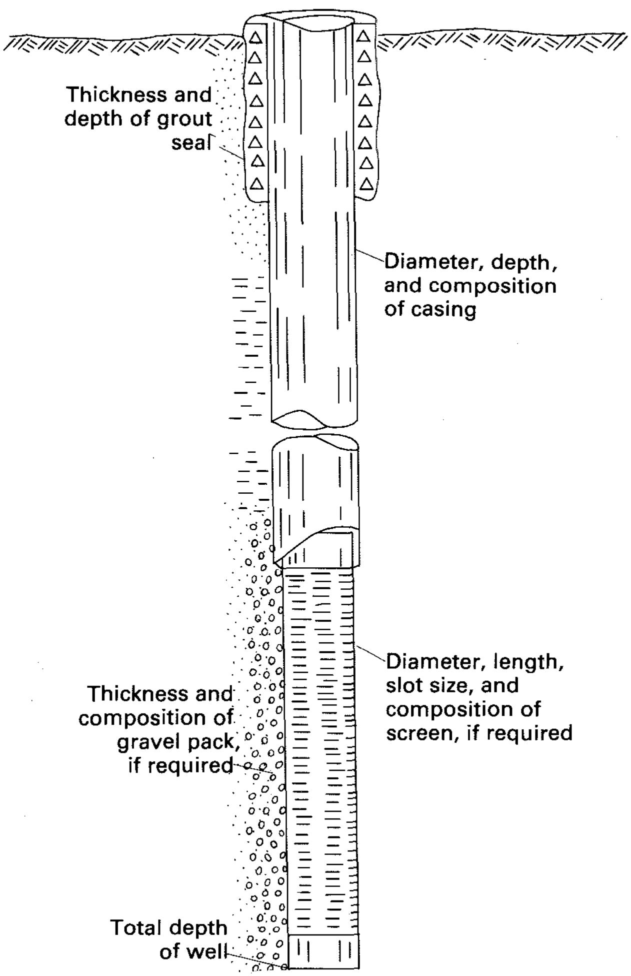
The spontaneous potential log (which is usually referred to as the SP log) is a record of the differences in the voltages of an electrode at the land surface and an electrode in the borehole. Variations in voltage occur as a result of electrochemical and other spontaneous electrical effects. The SP graph is relatively featureless in shallow water wells that penetrate only the freshwater zone. The right-hand boundary of an SP log generally indicates impermeable beds such as clay, shale, and bedrock. The left-hand boundary generally indicates sand, cavernous limestone, and other permeable layers.

The *resistivity log* is a record of the resistance to the flow of an alternating electric current offered by the rock layers and their contained fluids and the fluid in the borehole. Several different electrode arrangements are used to measure the resistivity of different volumes of material, but the arrangement most commonly used by the water-well industry is referred to as the single-point electrode. The resistivity of water-bearing material depends primarily on the salt content of the water and the porosity of the material. Clay layers normally have a low resistivity because of their large porosity, and the water that they contain tends to be relatively highly mineralized. In contrast, sand layers saturated with freshwater tend to have a high resistivity. Sand layers containing salty water, on the other hand, tend to have a low resistivity resembling that of clay layers. Such layers tend to have a strongly negative spontaneous potential that, viewed together with the resistivity, aids in identification of the layers.

Several other types of geophysical logs are available, including gamma-ray logs that record the rate of emission of gamma rays by different rock layers. In fact, geophysical logging is a complex topic that has been developed, largely by the oil industry, into an advanced technical field. It is being utilized to an increasing extent by the water-well industry, especially in conjunction with the construction of large-yield wells by the hydraulic rotary method.

It is also important, either during well construction or following geophysical logging, to collect, for chemical analyses, water samples from the permeable zones that may supply water to the completed well. The chemical analyses made on these samples should include the concentration of any constituents that are known to be a problem in other supply wells drawing from the aquifer. These constituents might include iron, manganese, chloride, sulfate, nitrate, total dissolved solids, and others. (See "Quality of Ground Water.")

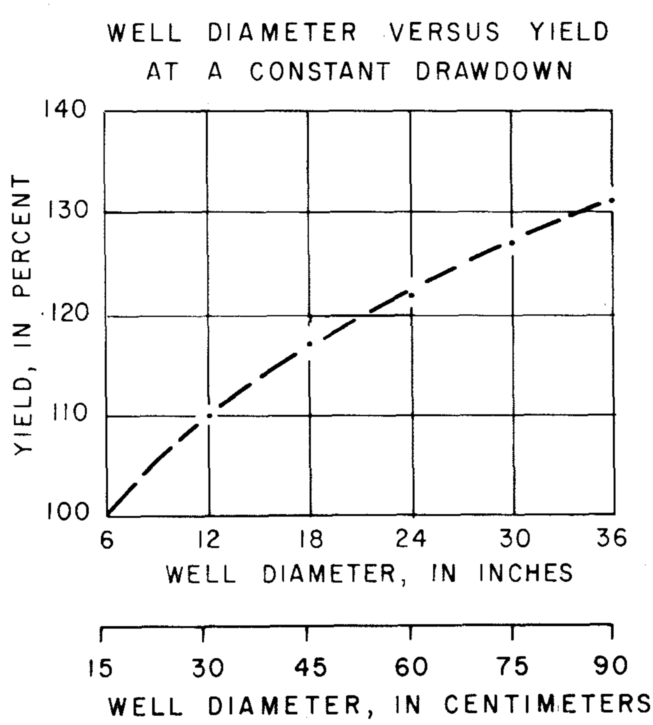
WATER-WELL DESIGN



(1)

Water-well design is the first step in the construction of large-yield wells, such as those required by municipalities and industries. Before the initial design is started, it is necessary to know the yield expected from the well, the depth to aquifers underlying the area, the composition and hydraulic characteristics of those aquifers, and the quality of water in the aquifers. If information on an aquifer is not already available from other wells in the area, it will be necessary to construct a test well before completing the design. The completed design should specify the diameter, the total depth of the well and the position of the screen or open-hole sections, the method of construction, the materials to be used in the construction, and, if a gravel pack is required, its thickness and composition (1).

The *well diameter* is determined primarily by two factors—the desired yield and the depth to the source aquifer. The diameter has a relatively insignificant effect on the yield (2). For example, doubling the diameter from 15 to 30 centimeters results in only about a 10 percent increase in yield.



(2)

The primary effect of well diameter on yield is related to the size of the pump that can be installed, which, in turn, determines the pumping rate. Data on pumping rate, pump size, and well diameter are given in table 1. In some designs, the upper part of the well is made larger than the remainder of the well in order to accommodate the pump.

Table 1. Data on yield, pump size, and well diameter
[ID, inside diameter; OD, outside diameter]

Anticipated well yield			Nominal size of pump bowls (in.)	Optimum well diameter (in.)
In gal min^{-1}	In ft^3 min^{-1}	In m^3 min^{-1}		
Less than 100	Less than 13	Less than 0.38	4	6 ID
75–175	10–23	.28–.66	5	8 ID
150–400	20–53	.57–1.52	6	10 ID
350–650	47–87	1.33–2.46	8	12 ID
600–900	80–120	2.27–3.41	10	14 OD
850–1,300	113–173	3.22–4.93	12	16 OD
1,200–1,800	160–240	4.55–6.82	14	20 OD
1,600–3,000	213–400	6.06–11.37	16	24 OD

The screen diameter and length, the slot size, and the pumping rate determine the velocity at which water passes through the screen (that is, the so-called "entrance velocity"). The entrance velocity should not normally exceed about 6 ft min^{-1} (1.8 m min^{-1}). If the anticipated yield in cubic feet per minute shown in table 1 is divided by 6 ft min^{-1}, the result is the minimum open area of screen needed in square feet.[1] Because screen openings are partially blocked by aquifer or gravel-packed material, some well drillers increase the open area needed by 50 to 100 percent to assure that entrance velocities will not be excessive.

The amount of open area per unit length of well screen depends on the diameter, the slot size, and the type of screen. Table 2 shows, for example, the open area of screens manufactured by the Edward E. Johnson Co.[2] If the open area needed in square feet is divided by the open area per linear foot, the result is the length of screen, in feet, required to provide the yield without exceeding the recommended entrance velocity.

[1]Because dimensions of screens manufactured in the United States are still expressed in inches or feet, these units will be used in this discussion. SI units will be added only where it is useful to do so.

[2]The use of a company name is for identification purposes only and does not imply endorsement by the U.S. Geological Survey.

The depth to the source aquifer also affects the well diameter to the extent that wells expected to reach aquifers more than a few hundred feet below land surface must be large enough to accept the larger diameter cable tool or drill rods required to reach these depths.

The *total depth* of a well depends on the depth below land surface to the lowest water-bearing zone to be tapped.

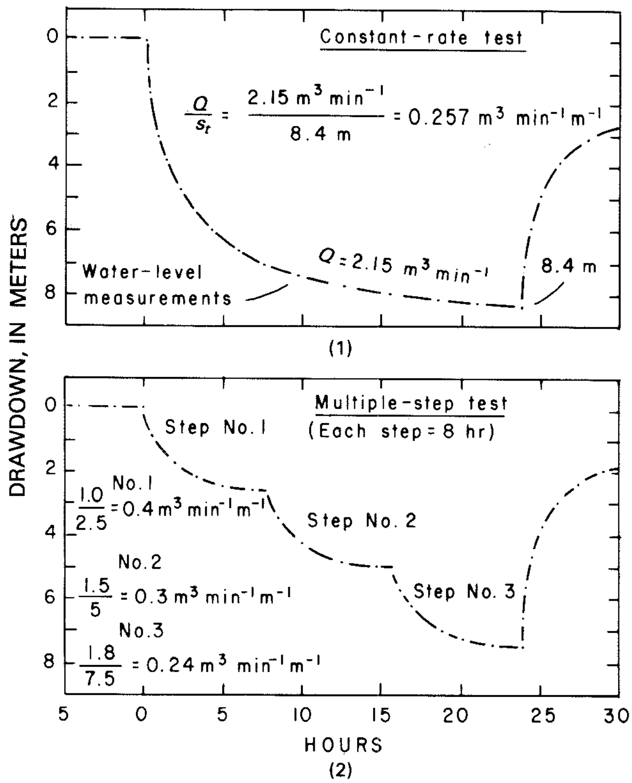
Table 2. Open areas of Johnson well screens
[*n* denotes width of screen opening in thousandths (1/1,000) of an inch. For example, slot no. 10 indicates an opening 10/1,000 or 0.01 inch]

Nominal screen diameter (in.)	Open areas per linear foot of screen for slot no. *n* (ft^2)						
	10	20	40	60	80	100	150
4	0.17	0.30	0.47	0.60	0.68	0.64	0.76
6	.17	.32	.53	.69	.81	.92	.97
8	.22	.41	.69	.90	1.05	1.19	1.28
10	.28	.51	.87	.96	1.15	1.30	1.60
12	.26	.50	.87	1.13	1.37	1.55	1.89
14	.30	.56	.96	1.26	1.53	1.74	2.11
16	.34	.64	1.11	1.45	1.75	1.98	2.42

The *position of the screen* depends on the thickness and composition of the source aquifer and whether the well is being designed to obtain the maximum possible yield. Because withdrawals from unconfined aquifers result in dewatering of the aquifers, wells in these aquifers are normally screened only in the lower part in order to obtain the maximum available drawdown. In confined aquifers, screens are set either in the most permeable part of the aquifer or, where vertical differences in hydraulic conductivity are not significant, in the middle part of the aquifer.

The length of the screen specified in the well design depends on the thickness of the aquifer, the desired yield, whether the aquifer is unconfined or confined, and economic considerations. When an attempt is being made to obtain the maximum available yield, screens are normally installed in the lower 30 to 40 percent of unconfined aquifers and in the middle 70 to 80 percent of confined aquifers.

WELL-ACCEPTANCE TESTS AND WELL EFFICIENCY



Many supply-well contracts require a "guaranteed" yield, and some stipulate that the well reach a certain level of "efficiency." Most contracts also specify the length of the "drawdown test" that must be conducted to demonstrate that the yield requirement is met. For example, many States require that tests of public-supply wells be at least 24 hours. Tests of most industrial and irrigation wells probably do not exceed about 8 hours.

Well-acceptance tests, if properly conducted, not only can confirm the yield of a well and the size of the production pump that is needed but can also provide information of great value in well operation and maintenance. Such tests should, therefore, be conducted with the same care as aquifer tests made to determine the hydraulic characteristics of aquifers. A properly conducted test will include:

1. Determination of well interference from nearby pumping wells, based on accurate water-level measurements made before the drawdown test.
2. A pumping rate that is either held constant during the entire test (1) or increased in steps of equal length (2). The pumping rate during each step should be held constant, and the length of each step should be at least 2 hours.

Of these requirements, the constant, carefully regulated pumping rate or rates and the accurate water-level measurements are the most important. When a constant-rate well-acceptance test has been completed, the drawdown data can be analyzed to determine the aquifer transmissivity. (See "Single-Well Tests.")

Many well-acceptance tests are made with temporary pump installations, usually powered with a gasoline or diesel engine. Instead of maintaining a constant rate for the duration of the test, the engine is frequently stopped to add fuel or to check the oil level or for numerous other reasons. The rate may also be increased and decreased on an irregular, unplanned schedule or, more commonly, gradually reduced during the test in an effort to maintain a pumping level above the pump intake. In such tests, the "yield" of the well is normally reported to be the final pumping rate.

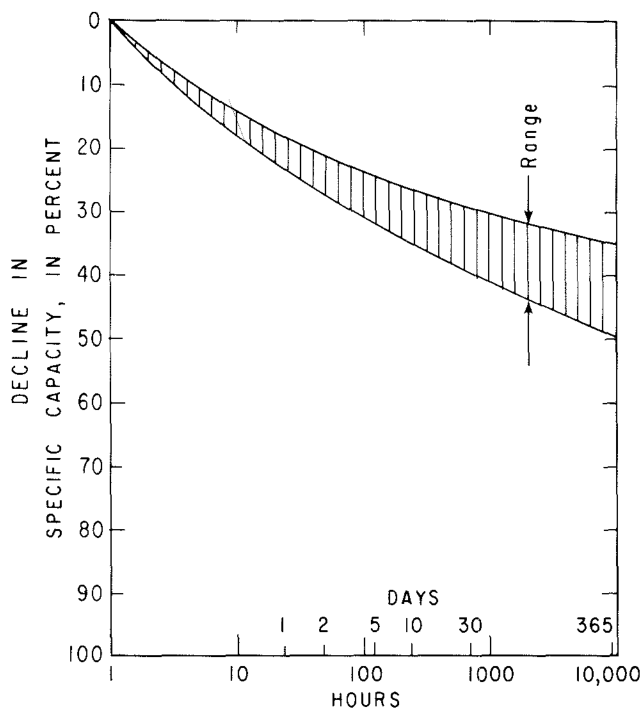
Determining the long-term yield of a well from data collected during a short-period well-acceptance test is one of the most important, practical problems in ground-water hydrology. Two of the most important factors that must be considered are the extent to which the yield will decrease if the well is pumped continuously for periods longer than the test period and the effect on the yield of changes in the static (regional) water level from that existing at the time of the test.

When data are available only from the production well and when the pumping rate was not held constant during the acceptance test, the estimate of the long-term yield must usually be based on an analysis of specific-capacity data. *Specific capacity* is the yield per unit of drawdown and is determined by dividing the pumping rate at any time during the test by the drawdown at the same time. Thus,

$$\text{specific capacity} = \frac{\text{pumping rate}}{\text{drawdown}} = \frac{Q}{s_t} \qquad (1)$$

Before the development of steady-state conditions, a part of the water pumped from an aquifer is derived from storage. The time required for steady-state conditions to develop depends largely on the distance to and characteristics of the recharge and discharge areas and the hydraulic characteristics of the aquifer. The time required to reach a steady state is independent of the pumping rate. At some places in some aquifers, a steady-state condition will be reached in several days, whereas, in others, six months to a year may be required; in some arid areas, a steady-state condition may never be achieved. Depending on the length of the well-acceptance test and the period required to reach a steady-state condition, it may be appropriate, in estimating the long-term yield of a well, to use a specific capacity smaller than that determined during the test.

DECLINE IN SPECIFIC CAPACITY WITH TIME
AT A CONTINUOUS PUMPING RATE



(3)

Sketch 3 shows the decline in specific capacity with time when a well is pumped continuously at a constant rate and all the water is derived from storage in an isotropic and homogeneous aquifer. For convenience in preparing the sketch, a value of 100 percent was assigned to the specific capacity 1 hour after the pump was started. The rate at which the specific capacity decreases depends on the decline of the water level due to depletion of storage and on the hydraulic characteristics of the aquifer. Differences in the rate for different aquifers are indicated by the width of the band on the sketch. When withdrawals are derived entirely from storage, the specific capacity will decrease about 40 percent during the first year.

In predicting the long-term yield of a well, it is also necessary to consider changes in the static water level resulting from seasonal and long-term variations in recharge and declines due to other withdrawals from the aquifer. The long-term yield is equal to the specific capacity, determined from the well-acceptance test, and reduced as necessary to compensate for the long-term decline discussed in the above paragraph, multiplied by the available drawdown.

The *available drawdown* at the time of a well-acceptance test is equal to the difference between the static water level at that time and the lowest pumping level that can be imposed on the well. The lowest pumping level in a screened well is normally considered to be a meter or two above the top of the screen. In an unscreened (open-hole) well, it may be at the level of either the highest or the lowest water-bearing opening penetrated by the well. The choice of the highest or the lowest opening depends on the chemical composition of the water and whether water cascading from openings above the pumping level results in precipitation of minerals on the side of the well and on the pump intake. If such precipitation is expected, the maximum pumping level should not be below the highest opening. The yield of a well is not increased by a pumping level below the lowest opening, and the maximum yield may, in fact, be attained at a much higher level.

To predict the maximum continuous long-term yield, it is necessary to estimate how much the static water level, and thus the available drawdown, may decline from the position that it occupied during the acceptance test. Records of water-level fluctuations in long-term observation wells in the area will be useful in this effort.

Well efficiency is an important consideration both in well design and in well construction and development. The objective, of course, is to avoid excessive energy costs by designing and constructing wells that will yield the required water with the least drawdown.

Well efficiency can be defined as the ratio of the drawdown (s_a) in the aquifer at the radius of the pumping well to the drawdown (s_t) inside the well. (See "Single-Well Tests.") Thus, the equation

$$E = \frac{s_a}{s_t} \times 100 \tag{2}$$

expresses well efficiency as a percentage.

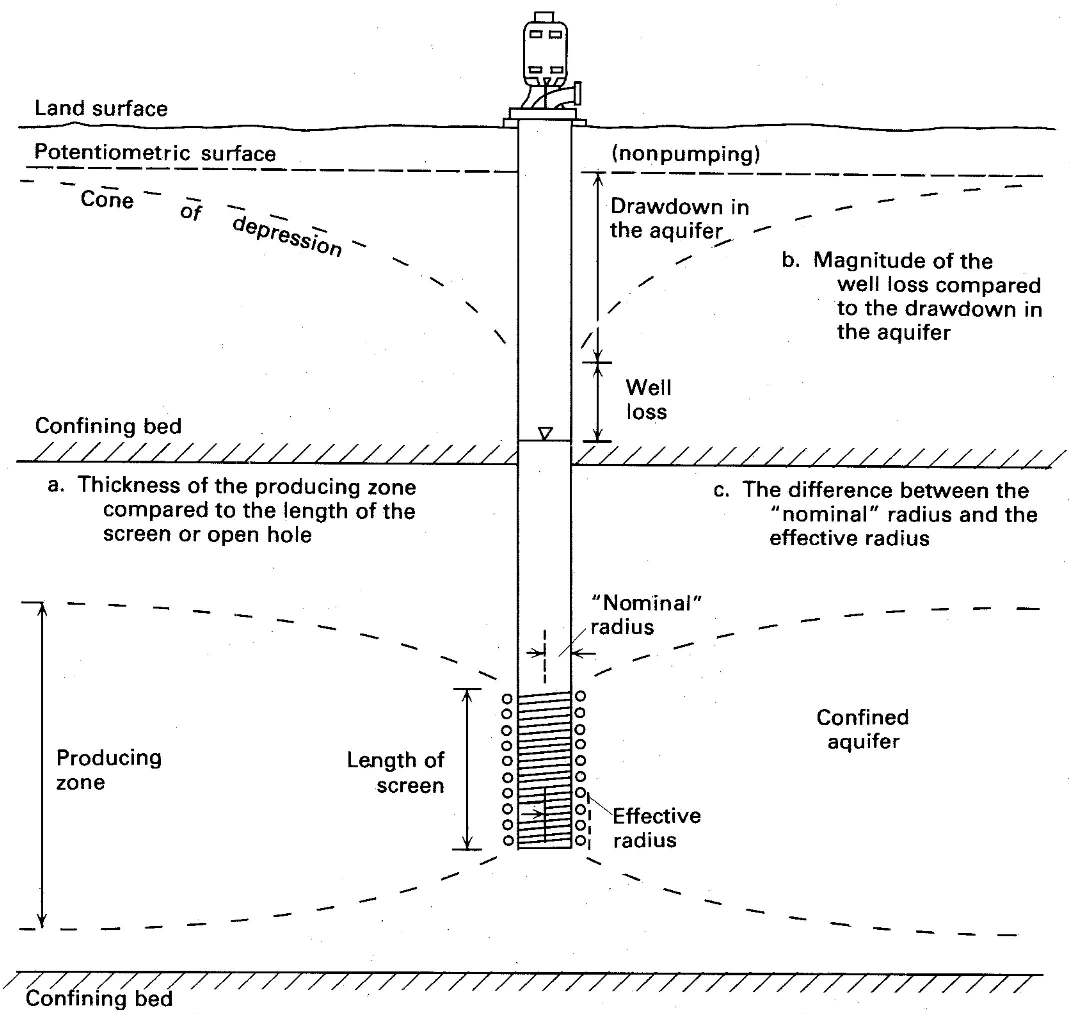
Drawdowns in pumping wells are measured during well-acceptance tests. Determining the drawdown in the aquifer is a much more difficult problem. It can be calculated if the hydraulic characteristics of the aquifer, including the effect of boundary conditions, are known.

The difference between s_t and s_a is attributed to head losses as water moves from an aquifer into a well and up the well bore. These well losses can be reduced by reducing the entrance velocity of the water, which can be done by installing the maximum amount of screen and pumping at the lowest acceptable rate. Tests have been devised to determine well losses, and the results can be used to determine well efficiency. However, these tests are difficult to conduct and are not widely used. Because of difficulties in determining s_a, well efficiency is generally specified in terms of an "optimum" specific capacity based on other producing wells in the vicinity.

Under the best conditions, an efficiency of about 80 percent is the maximum that is normally achievable in most screened wells. Under less than ideal conditions, an efficiency of 60 percent is probably more realistic.

SPECIFIC CAPACITY AND TRANSMISSIVITY

FACTORS AFFECTING ESTIMATES OF TRANSMISSIVITY
BASED ON SPECIFIC CAPACITY



FACTORS AFFECTING ESTIMATES OF TRANSMISSIVITY
BASED ON SPECIFIC CAPACITY

The specific capacity of a well depends both on the hydraulic characteristics of the aquifer and on the construction and other features of the well. Values of specific capacity, available for many supply wells for which aquifer-test data are not available, are widely used by hydrologists to estimate transmissivity. Such estimates are used to evaluate regional differences in transmissivity and to prepare transmissivity maps for use in models of ground-water systems.

The factors that affect specific capacity include:

1. The transmissivity of the zone supplying water to the well, which, depending on the length of the screen or open hole, may be considerably less than the transmissivity of the aquifer.
2. The storage coefficient of the aquifer.
3. The length of the pumping period.
4. The effective radius of the well, which may be significantly greater than the "nominal" radius.
5. The pumping rate.

The Theis equation can be used to evaluate the effect of the first four factors on specific capacity. The last factor, pumping rate, affects the well loss and can be determined only from a stepped-rate test or an aquifer test in which drawdowns are measured in both the pumping well and observation wells.

The Theis equation, modified for the determination of transmissivity from specific capacity, is

$$T = \frac{W(u)}{4\pi} \times \frac{Q}{s} \qquad (1)$$

where T is transmissivity, Q/s is specific capacity, Q is the pumping rate, s is the drawdown, and $W(u)$ is the well function of u, where

$$u = \frac{r^2S}{4Tt} \qquad (2)$$

where r is the effective radius of the well, S is the storage coefficient, and t is the length of the pumping period preceding the determination of specific capacity.

For convenience in using equation 1, it is desirable to express $W(u)/4\pi$ as a constant. To do so, it is first necessary to determine values for u and, using a table of values of u (or $1/u$) and $W(u)$, determine the corresponding values for $W(u)$.

Values of u are determined by substituting in equation 2 values of T, S, r, and t that are representative of conditions in the area. To illustrate, assume, in an area under investigation and for which a large number of values of specific capacity are available, that:

1. The principal aquifer is confined, and aquifer tests indicate that it has a storage coefficient of about 2×10^{-4} and a transmissivity of about 11,000 $ft^2\ d^{-1}$.
2. Most supply wells are 8 in. (20 cm) in diameter (radius, 0.33 ft).
3. Most values of specific capacity are based on 12-hour well-acceptance tests ($t = 0.5$ d).

Substituting these values in equation 2, we obtain

$$u = \frac{r^2S}{4Tt} = \frac{(0.33\ \text{ft})^2\times(2\times10^{-4})}{4\times(11{,}000\ \text{ft}^2\ \text{d}^{-1})\times0.5\ \text{d}}$$

$$u = \frac{2.22\times10^{-5}\ \text{ft}^2}{2.2\times10^{4}\ \text{ft}^2} = 1.01\times10^{-9}$$

A table of values of $W(u)$ for values of $1/u$ is contained in the section of this report entitled "Aquifer Tests." Therefore, the value of u determined above must be converted to $1/u$, which is 9.91×10^8, and this value is used to determine the value of $W(u)$. Values of $W(u)$ are given for values of $1/u$ of 7.69×10^8 and 10×10^8 but not for 9.91×10^8. However, the value of 10 is close enough to 9.91 for the purpose of estimating transmissivity from specific capacity. From the table, we determine that, for a value of $1/u$ of 10×10^8, the value of $W(u)$ is 20.15. Substituting this value in equation 1, we find the constant $W(u)/4\pi$ to be 1.60.

Equation 1 is in consistent units. However, transmissivity is commonly expressed in the United States in units of square feet per day, pumping rates are reported in units of gallons per minute, and drawdowns are measured in feet. To obtain an equation that is convenient to use, it is desirable to convert equation 1 to these inconsistent units. Thus

$$T = 1.60\times\frac{1{,}440\ \text{min}}{\text{d}}\times\frac{\text{ft}^3}{7.48\ \text{gal}}\times\frac{Q}{s}$$

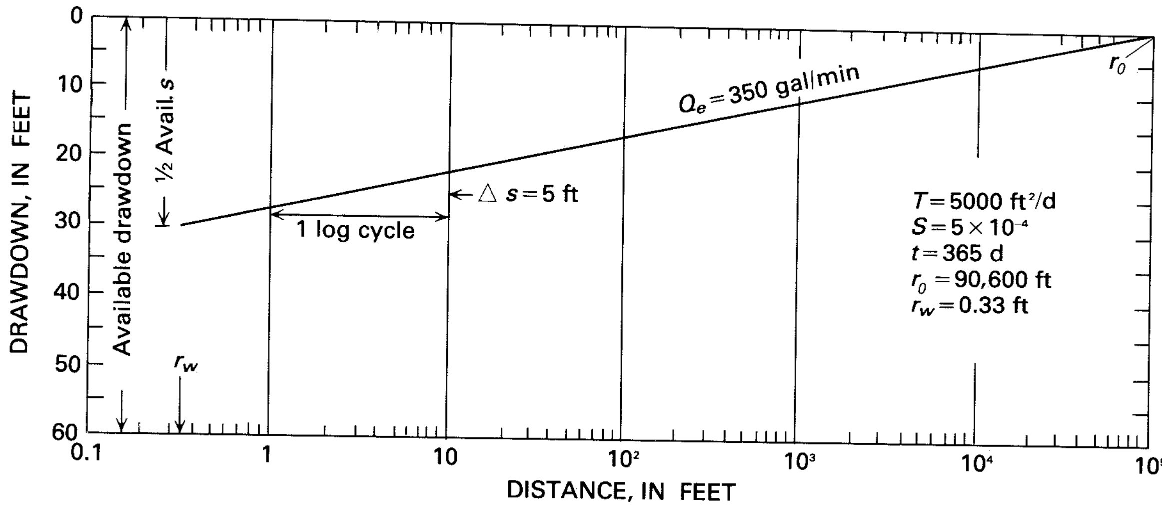
$$T = 308\ \frac{Q}{s}\ \text{or}\ 300\frac{Q}{s}\ \text{(rounded)} \qquad (3)$$

Many readers will find it useful at this point to substitute different values of T, S, r, and t in equation 2 to determine how different values affect the constant in equation 3. In using equation 3, modified as necessary to fit the conditions in an area, it is important to recognize its limitations. Among the most important factors that affect its use are the accuracy with which the thickness of the zone supplying water to the well can be estimated, the magnitude of the well loss in comparison with drawdown in the aquifer, and the difference between the "nominal" radius of the well and its effective radius.

Relative to these factors, the common practice is to assume that the value of transmissivity estimated from specific capacity applies only to the screened zone or to the open hole. To apply this value to the entire aquifer, the transmissivity is divided by the length of the screen or open hole (to determine the hydraulic conductivity per unit of length), and the result is multiplied by the entire thickness of the aquifer. The value of transmissivity determined by this method is too large if the zone supplying water to the well is thicker than the length of the screen or the open hole. Similarly, if the effective radius of the well is larger than the "nominal" radius (assuming that the "nominal" radius is used in equation 2), the transmissivity based on specific capacity again will be too large.

On the other hand, if a significant part of the drawdown in the pumping well is due to well loss, the transmissivity based on specific capacity will be too small. Whether the effect of all three of these factors cancels depends on the characteristics of both the aquifer and the well. Where a sufficient number of aquifer tests have been conducted, it may be feasible to utilize the results to modify the constant in equation 3 to account for the effect of these factors.

WELL-FIELD DESIGN



(1)

The development of moderate to large supplies of water from most aquifers requires more than one well; in other words, it requires what is commonly referred to as a *well field*. Consequently, the design of well fields is an important problem in ground-water development. The objective of well-field design is to obtain the required amount of water for the least cost, including the initial construction cost of wells and pipelines, the cost of operation and maintenance, and the cost of well replacement.

The final product of a design is a plan showing the arrangement and spacing of wells and specifications containing details on well construction and completion, including information on well diameter, depth, and position of screens or open hole, the type of casing and screens, and the type, size, and setting of pumps.

The key elements in well-field design are the total quantity of water to be obtained from the field, the rate at which each well can be pumped (which determines the number of wells that will be required), and the spacing of the wells.

The *pumping rate* for each well can be estimated with Jacob's modification of the Theis equation. (See "Distance-Drawdown Analysis.") It depends on the transmissivity and storge coefficient of the aquifer, the distance to and nature of lateral boundaries, the hydraulic characteristics of confining beds, the available drawdown, and the pumping period. For the purpose of this discussion, we will not consider the effect of boundaries or confining beds. (For a discussion of available drawdown, see "Well Interference" and "Well-Acceptance Tests and Well Efficiency.") The *pumping period* is normally taken as 1 year. To determine the pumping rate, Jacob's equations are solved as follows:

$$r_0^2 = \frac{2.25Tt}{S} \qquad (1)$$

$$Q_e = 2.7T\Delta s \qquad (2)$$

where r_0 is the distance from the pumping well, in meters (or feet), to the point of zero drawdown on a semilogarithmic graph in which drawdown is on the arithmetic scale and distance is on the logarithmic scale, T is aquifer transmissivity, in square meters per day (or square feet per day), t is 365 days (1 year), S is the aquifer storage coefficient (dimensionless), Δs is the drawdown, in meters (or feet), across one log cycle along a line connecting point r_0 and a point at the proposed radius of the pumping well at which the drawdown equals about half the available drawdown,[1] and Q_e is the first estimate of the pumping rate in cubic meters per day (or cubic feet per day). To convert to gallons per minute, when Q_e is in cubic meters per day, divide by 5.45 (when Q_e is in cubic feet per day, divide by 192).

The estimated pumping rate Q_e is divided into the total quantity of water needed from the well field in order to determine the number of wells that will be needed. The next step is to determine the optimum *well spacing*. This determination involves both hydrologic and economic considerations. The hydrologic considerations include the following:

1. The minimum distance between pumping wells should be at least twice the aquifer thickness if the wells are open to less than about half the aquifer thickness.
2. Wells near recharging boundaries should be located along a line parallel to the boundary and as close to the boundary as possible.
3. Wells near impermeable boundaries should be located along a line perpendicular to the boundary and as far from the boundary as possible.

[1]At this point, we use half the available drawdown in order to get a first estimate of well loss and well interference. If we determine that, at a pumping rate of Q_e, the drawdown in the aquifer is less than the available drawdown and the drawdown in the well is above the top of the screen, we can assume a larger value of s and recompute Q_e. It is important also to note that, in the initial determination of available drawdown, the seasonal fluctuation of static water level must be considered.

The primary economic considerations involved in well spacing include the cost of wells and pumps, power costs, and the cost of interconnecting pipelines and powerlines. The closer wells are spaced, the smaller the yield of each well because of well interference. The smaller yield of closely spaced wells means that more wells and well pumps are required, and power costs are higher. The cost of the additional wells and the larger pumping costs must be evaluated in relation to the cost of shorter interconnecting pipelines and powerlines.

Sketch 1 shows a distance-drawdown graph for a pumping well at the end of a continuous pumping period of one year for an aquifer having a transmissivity (T) of 5,000 $ft^2\ d^{-1}$ (465 $m^3\ d^{-1}$), a storage coefficient (S) of 5×10^{-4}, and an available drawdown of 60 ft (18 m). The assumed radius of the pumping well (r_w) is 0.33 ft (diameter, 8 in. or 20 cm). When one-half the available drawdown is used, along with the other values as stated, equation 2 yields an estimated pumping rate (Q_e) of 350 gal min^{-1} or 504,000 gal d^{-1}.[2]

To illustrate the use of sketch 1 in analyzing the well-spacing problem, we will assume that a yield of 1,500,000 gal d^{-1} (1,040 gal min^{-1}) is desired from the aquifer. This yield can be obtained from three wells producing 500,000 gal d^{-1} (350 gal min^{-1}) each. Assume that the wells are located on a straight line and are numbered 1, 2, and 3. Well 2, being in the middle, will obviously have the most well interference and, therefore, the largest drawdown. How close can it be to wells 1 and 3 without its drawdown exceeding the available drawdown of 60 ft?

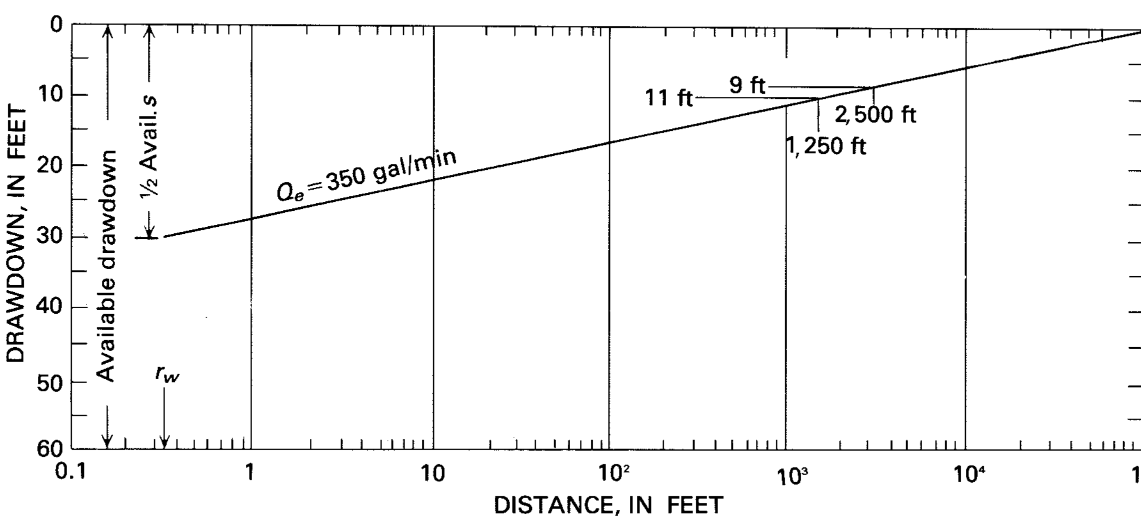
When well 2 is pumped at a rate of 350 gal min^{-1}, the drawdown in the aquifer at the radius of the well will be one-half the available drawdown, or 30 ft. The remaining 30 ft of the available drawdown must be apportioned between well loss in well 2 and interference from wells 1 and 3. According to sketch 1, if well 2 were 100 percent efficient, its specific capacity would be

$$\frac{350 \text{ gal min}^{-1}}{30 \text{ ft}} = 11.7 \text{ gal min}^{-1} \text{ ft}^{-1}$$

We will assume, however, that well 2 will be only 80 percent efficient. If so, its specific capacity will be

$$\frac{11.7 \text{ gal min}^{-1} \text{ ft}^{-1}}{100 \text{ percent}} = \frac{X}{80 \text{ percent}} = 9.4 \text{ gal min}^{-1} \text{ ft}^{-1}$$

and a yield of 350 gal min^{-1} will produce a drawdown in well 2 of about 37 ft (350/9.4). Subtracting 37 ft from 60 ft leaves a difference of 23 ft, which can be assigned to well interference from wells 1 and 3. If fractional feet are ignored, the amount of interference by each well is about 11 ft.

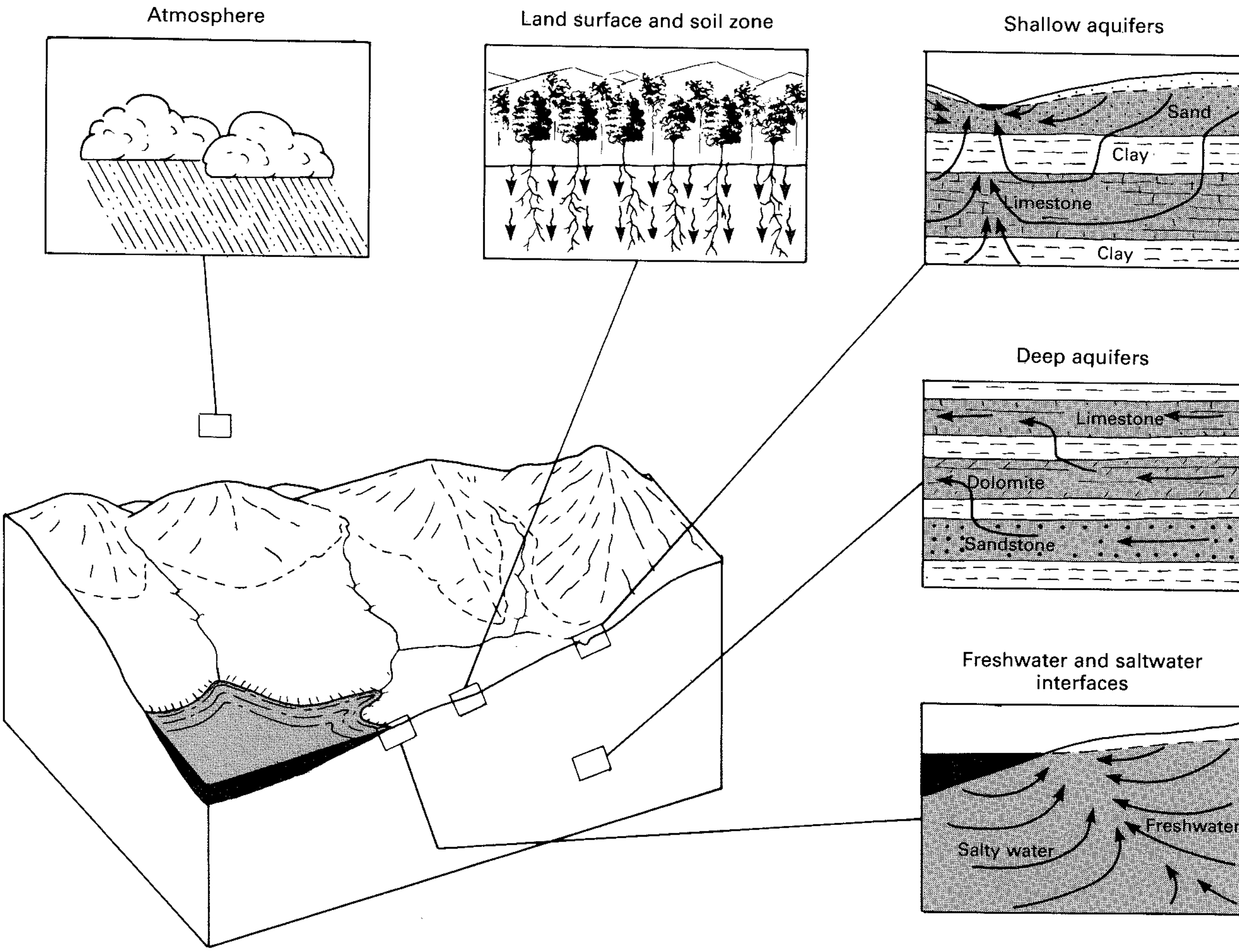


(2)

Sketch 2 shows that a well pumping 350 gal min^{-1} from the aquifer will produce a drawdown of 11 ft at a distance of about 1,250 ft. Therefore, the spacing between wells 1 and 2 and between wells 2 and 3 would have to be 1,250 ft in order not to exceed the available drawdown at well 2. With this spacing, wells 1 and 3 would be 2,500 ft apart. Sketch 2 shows the drawdown at 2,500 ft to be about 9 ft. Consequently, the drawdowns in both wells 1 and 3 would be 58 ft, or about 2 ft less than the drawdown in well 2.

[2]Inch-pound units are used in this example for the convenience of those readers who are not yet accustomed to using metric units.

QUALITY OF GROUND WATER



THE CHEMICAL CHARACTERISTICS OF GROUND WATER ARE DETERMINED BY THE CHEMICAL AND BIOLOGICAL REACTIONS IN THE ZONES THROUGH WHICH THE WATER MOVES

Water consists of two atoms of hydrogen and one of oxygen, which give it a chemical formula of H_2O. Water frequently is referred to as the universal solvent because it has the ability to dissolve at least small amounts of almost all substances that it contacts. Of the domestic water used by man, ground water usually contains the largest amounts of dissolved solids. The composition and concentration of substances dissolved in unpolluted ground water depend on the chemical composition of precipitation, on the biologic and chemical reactions occurring on the land surface and in the soil zone, and on the mineral composition of the aquifers and confining beds through which the water moves.

The concentrations of substances dissolved in water are commonly reported in units of weight per volume. In the International System (SI), the most commonly used units are milligrams per liter. A milligram equals 1/1,000 (0.001) of a gram, and a liter equals 1/1,000 of a cubic meter, so that 1 mg/L equals 1 gram m^{-3}.[1] Concentrations of substances in water were reported for many years in the United States in units of weight per weight. Because the concentration of most substances dissolved in water is relatively small, the weight per weight unit commonly used was parts per million (ppm). In inch-pound units, 1 ppm is equal to 1 lb of a substance dissolved in 999,999 lb of water, the weight of the solution thus being 1 million pounds.

The quality of ground water depends both on the substances dissolved in the water and on certain properties and characteristics that these substances impart to the water. Table 1 contains information on dissolved inorganic substances that normally occur in the largest concentrations and are most likely to affect water use. Table 2 lists other characteristics of water that are commonly reported in water analyses and that may affect water use. Dissolved constituents for which concentration limits have been established for drinking water are discussed in "Pollution of Ground Water."

[1]To put these units in possibly more understandable terms, 1 mg/L equals 1 oz of a substance dissolved in 7,500 gal of water.

Table 1. Natural inorganic constituents commonly dissolved in water that are most likely to affect use of the water

Substance	Major natural sources	Effect on water use	Concentrations of significance (mg/L)[1]
Bicarbonate (HCO_3) and carbonate (CO_3)	Products of the solution of carbonate rocks, mainly limestone ($CaCO_3$) and dolomite ($CaMgCO_3$), by water containing carbon dioxide.	Control the capacity of water to neutralize strong acids. Bicarbonates of calcium and magnesium decompose in steam boilers and water heaters to form scale and release corrosive carbon dioxide gas. In combination with calcium and magnesium, cause carbonate hardness.	150–200
Calcium (Ca) and magnesium (Mg)	Soils and rocks containing limestone, dolomite, and gypsum ($CaSO_4$). Small amounts from igneous and metamorphic rocks.	Principal cause of hardness and ofr boiler scale and deposits in hot-water heaters.	25–50
Chloride (Cl)	In inland areas, primarily from seawater trapped in sediments at time of deposition; sition; in coastal areas, from seawater in contact with freshwater in productive aquifers.	In large amounts, increases corrosiveness of water and, in combination with sodium, gives water a salty taste.	250
Fluoride (F)	Both sedimentary and igneous rocks. Not widespread in occurrence.	In certain concentrations, reduces tooth decay; at higher concentrations, causes mottling of tooth enamel.	0.7–1.2[2]
Iron (Fe) and manganese (Mn)	Iron present in most soils and rocks; manganese less widely distributed.	Stain laundry and are objectionable in food processing, dyeing, bleaching, ice manufacturing, brewing, and certain other industrial processes.	Fe>0.3, Mn>0.05
Sodium (Na)	Same as for chloride. In some sedimentary rocks, a few hundred milligrams per liter may occur in freshwater as a result of exchange of dissolved calcium and magnesium for sodium in the aquifer materials.	See chloride. In large concentrations, may affect persons with cardiac difficulties, hypertension, and certain other medical conditions. Depending on the concentrations of calcium and magnesium also present in the water, sodium may be detrimental to certain irrigated crops.	69 (irrigation), 20–170 (health)[3]
Sulfate (SO_4)	Gypsum, pyrite (FeS), and other rocks containing sulfur (S) compounds.	In certain concentrations, gives water a bitter taste and, at higher concentrations, has a laxative effect. In combination with calcium, forms a hard calcium carbonate scale in steam boilers.	300–400 (taste), 600–1,000 (laxative)

[1]A range in concentration is intended to indicate the general level at which the effect on water use might become significant.
[2]Optimum range determined by the U.S. Public Health Service, depending on water intake.
[3]Lower concentration applies to drinking water for persons on a strict diet; higher concentration is for those on a moderate diet.

Table 2. Characteristics of water that affect water quality

Characteristic	Principal cause	Significance	Remarks
Hardness	Calcium and magnesium dissolved in the water.	Calcium and magnesium combine with soap to form an insoluble precipitate (curd) and thus hamper the formation of a lather. Hardness also affects the suitability of water for use in the textile and paper industries and certain others and in steam boilers and water heaters.	USGS classification of hardness (mg/L as $CaCO_3$): 0–60: Soft 61–120: Moderately hard 121–180: Hard More than 180: Very hard
pH (or hydrogen-ion activity)	Dissociation of water molecules and of acids and bases dissolved in water.	The pH of water is a measure of its reactive characteristics. Low values of pH, particularly below pH 4, indicate a corrosive water that will tend to dissolve metals and other substances that it contacts. High values of pH, particularly above pH 8.5, indicate an alkaline water that, on heating, will tend to form scale. The pH significantly affects the treatment and use of water.	pH values: less than 7, water is acidic; value of 7, water is neutral; more than 7, water is basic.
Specific electrical conductance	Substances that form ions when dissolved in water.	Most substances dissolved in water dissociate into ions that can conduct an electrical current. Consequently, specific electrical conductance is a valuable indicator of the amount of material dissolved in water. The larger the conductance, the more mineralized the water.	Conductance values indicate the electrical conductivity, in micromhos, of 1 cm^3 of water at a temperature of 25°C.
Total dissolved solids	Mineral substances dissolved in water.	Total dissolved solids is a measure of the total amount of minerals dissolved in water and is, therefore, a very useful parameter in the evaluation of water quality. Water containing less than 500 mg/L is preferred for domestic use and for many industrial processes.	USGS classification of water based on dissolved solids (mg/L): Less than 1,000: Fresh 1,000–3,000: Slightly saline 3,000–10,000: Moderately saline 10,000–35,000: Very saline More than 35,000: Briny

POLLUTION OF GROUND WATER

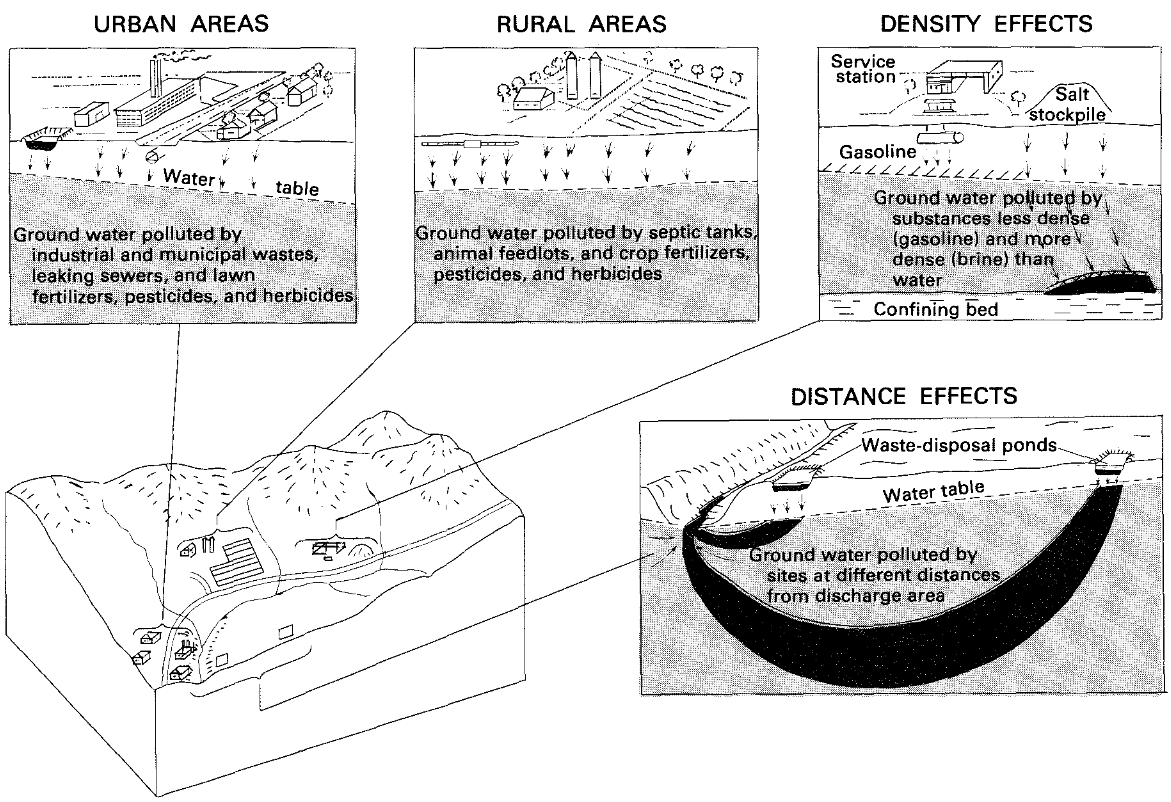
Pollution of ground water is receiving increased attention from both Federal and State regulatory agencies and from water users. As a result, pollution has been found to be much more widespread than we had believed only a few years ago. This attention has also resulted in widespread recognition of the facts that polluted ground water may pose a serious threat to health that is often not apparent to those affected and that purification of polluted ground-water systems may require centuries or the expenditure of huge sums of money. These facts alone make it imperative that the pollution of ground water by harmful substances absolutely be avoided to the maximum possible extent.

Pollution of ground water, as it is used in this discussion, refers to any deterioration in the quality of the water resulting from the activities of man. This definition includes saltwater encroachment into freshwater-bearing aquifers resulting from the artificial lowering of ground-water heads. That topic, however, is covered in a separate discussion. (See "Saltwater Encroachment.")

Most pollution of ground water results from the disposal of wastes on the land surface, in shallow excavations including septic tanks, or through deep wells and mines; the use of fertilizers and other agricultural chemicals; leaks in sewers, storage tanks, and pipelines; and animal feedlots. The magnitude of any pollution problem depends on the size of the area affected and the amount of the pollutant involved, the solubility, toxicity, and density of the pollutant, the mineral composition and hydraulic characteristics of the soils and rocks through which the pollutant moves, and the effect or potential effect on ground-water use.

Affected areas range in size from point sources, such as septic tanks, to large urban areas having leaky sewer systems and numerous municipal and industrial waste-disposal sites. Nearly all substances are soluble to some extent in water, and many chemical wastes are highly toxic even in minute concentrations. For example, table 1 lists the maximum concentrations of inorganic substances permitted in drinking-water supplies. Limits have also been established by the Environmental Protection Agency for radioactive and certain organic substances.

The density of a liquid substance—that is, the weight per unit volume of the substance relative to that of water—affects its underground movement. Densities range from those of petroleum products that are less dense than water to brines and other substances that are denser than water. Substances less dense than water tend to accumulate at the top of



GROUND-WATER POLLUTION OCCURS IN BOTH URBAN AND RURAL AREAS AND IS AFFECTED BY DIFFERENCES IN CHEMICAL COMPOSITION, BIOLOGICAL AND CHEMICAL REACTIONS, DENSITY, AND DISTANCE FROM DISCHARGE AREAS the saturated zone; if, like petroleum, they are immiscible, they will tend to spread in all directions as a thin film. Substances denser than water tend to move downward through the saturated zone to the first extensive confining bed.

The mineral composition and physical characteristics of soils and rocks through which pollutants move may affect the pollutants in several ways. If a pollutant enters the ground at a "point," it will be dispersed longitudinally and laterally in granular materials so that its concentration will be reduced in the direction of movement. (See "Saturated Flow and Dispersion.") Organic substances and other biodegradable materials tend to be broken down both by oxidation and by bacterial action in the unsaturated zone. Certain earth materials, especially clays and organic matter, may also absorb trace metals and certain complex organic pollutants and thereby reduce their concentration as they move through the underground environment.

The hydraulic characteristics of the soils and rocks determine the path taken by and the rate of movement of pollutants. Substances dissolved in water move with the water except to the extent that they are tied up or delayed by adsorption. Thus, the movement of pollutants tends to be through the most permeable zones; the farther their point of origin from a ground-water discharge area, the deeper they penetrate into the ground-water system and the larger the area ultimately affected.

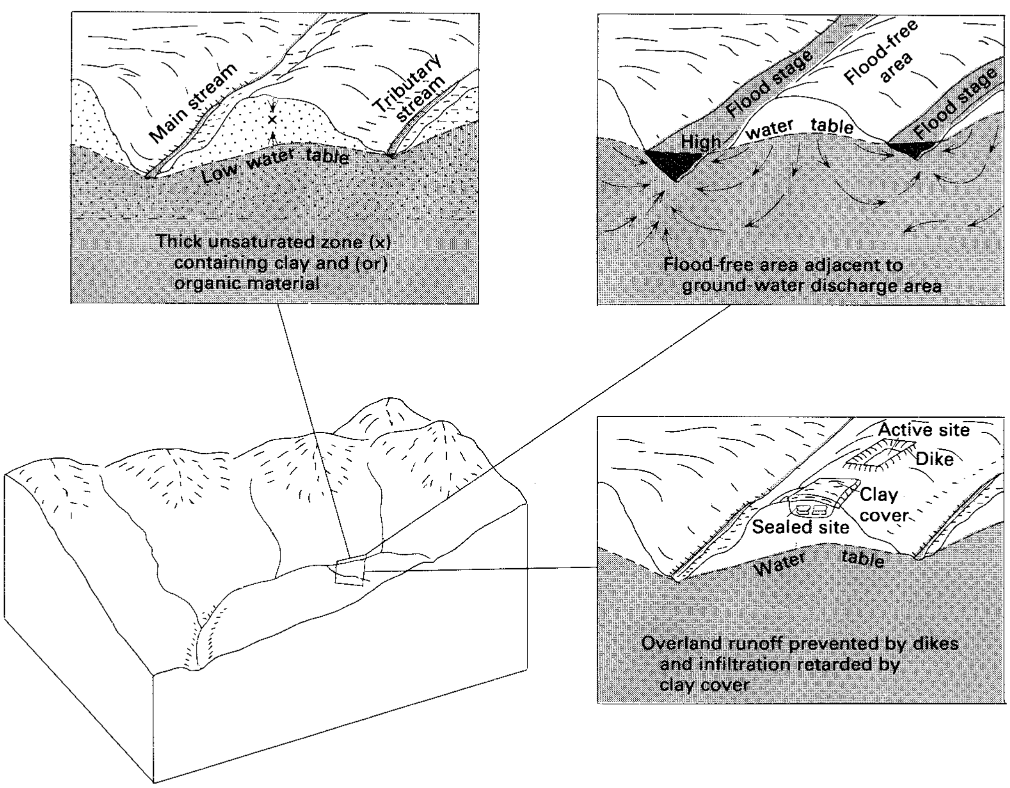
The factors related to the movement of pollutants discussed in the preceding paragraphs must be carefully considered in the selection of waste-disposal sites, animal feedlots, and sites for other operations that may cause ground-water pollution. With these factors in mind, it is obvious that significant ground-water pollution can be avoided only if waste-disposal sites are selected in such a way that:

1. Significant thicknesses of unsaturated material containing clay and (or) organic material are present.
2. Areas are as close as possible to places of natural ground-water discharge.
3. Overland runoff is excluded, and surface infiltration is held to the minimum possible amount.

Table 1. Maximum concentrations of inorganic constituents allowed in drinking water

[Data from U.S. Environmental Protection Agency (1977)]

Constituents	Concentration (mg/L)
Arsenic	0.05
Barium	1.
Cadmium	.010
Chromium	.05
Lead	.05
Mercury	.002
Nitrate (as N)	10.
Selenium	.01
Silver	.05



SELECTION OF WASTE-DISPOSAL SITES INVOLVES CONSIDERATION OF THE UNSATURATED ZONE, FLOOD DANGER, GROUND-WATER DISCHARGE, OVERLAND RUNOFF, AND INFILTRATION

SALTWATER ENCROACHMENT

In coastal areas, fresh ground water derived from precipitation on the land comes in contact with and discharges into the sea or into estuaries containing brackish water. The relation between the freshwater and the seawater, or brackish water, is controlled primarily by the differences in their densities.

The *density* of a substance is its mass per unit volume; thus, the density of water is affected by the amount of minerals, such as common salt (NaCl), that the water contains in solution. In metric units, the density of freshwater is about 1 gm cm^{-3}, and the density of seawater is about 1.025 gm cm^{-3}. Thus, freshwater, being less dense than seawater, tends to override or float on seawater.

On islands, such as the Outer Banks of North Carolina, precipitation forms a freshwater lens that "floats" on the underlying saltwater (1). The higher the water table stands above sea level, the thicker the freshwater lens. This relation between the height of the water table and the thickness of the freshwater lens was discovered, independently, by a Dutchman, Badon Ghyben, and a German, B. Herzberg, and is referred to as the *Ghyben-Herzberg relationship*. This relation, expressed as an equation, is

$$h_s = \frac{\rho_f}{\rho_s - \rho_f}(h_f) \qquad (1)$$

where h_s is the depth of freshwater below sea level, ρ_f is the density of freshwater, ρ_s is the density of seawater, and h_f is the height of the water table above sea level.

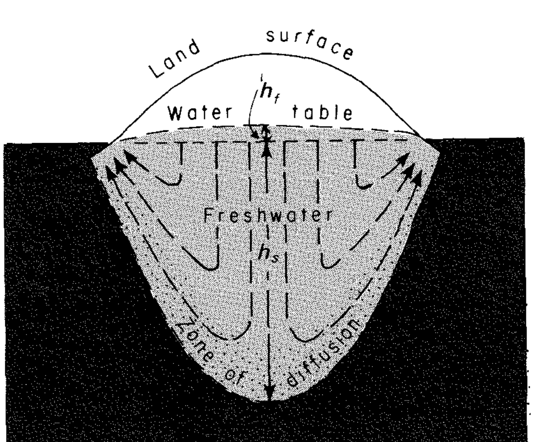
On the basis of equation 1 and the differences between the densities of freshwater and seawater, the freshwater zone should extend to a depth below sea level (h_s) equal to 40 times the height of the water table above sea level (h_f). The Ghyben-Herzberg relation applies strictly, however, only to a homogenous and isotropic aquifer in which the freshwater is static and is in contact with a tideless sea or body of brackish water.

Tides cause saltwater to alternately invade and retreat from the freshwater zone, the result being a zone of diffusion across which the salinity changes from that of freshwater to that of seawater (1). A part of the seawater that invades the freshwater zone is entrained in the freshwater and is flushed back to the sea by the freshwater as it moves to the sea to discharge.

Because both the seawater and the freshwater are in motion (not static), the thickness of the freshwater zone in a homogenous and isotropic aquifer is greater than that predicted by the Ghyben-Herzberg equation. On the other hand, in a stratified aquifer (and nearly all aquifers are stratified), the thickness of the freshwater lens is less than that predicted because of the head loss incurred as the freshwater moves across the least permeable beds.

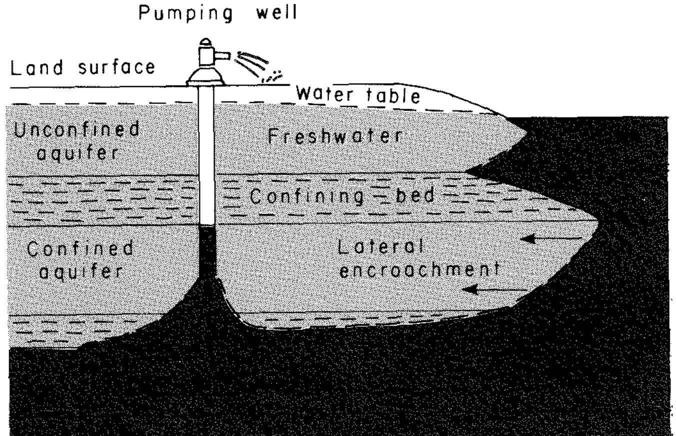
When freshwater heads are lowered by withdrawals through wells, the freshwater-saltwater contact migrates toward the point of withdrawals until a new balance is established (2). The movement of saltwater into zones previously occupied by freshwater is referred to as *saltwater encroachment*.

Freshwater lens floating on saltwater



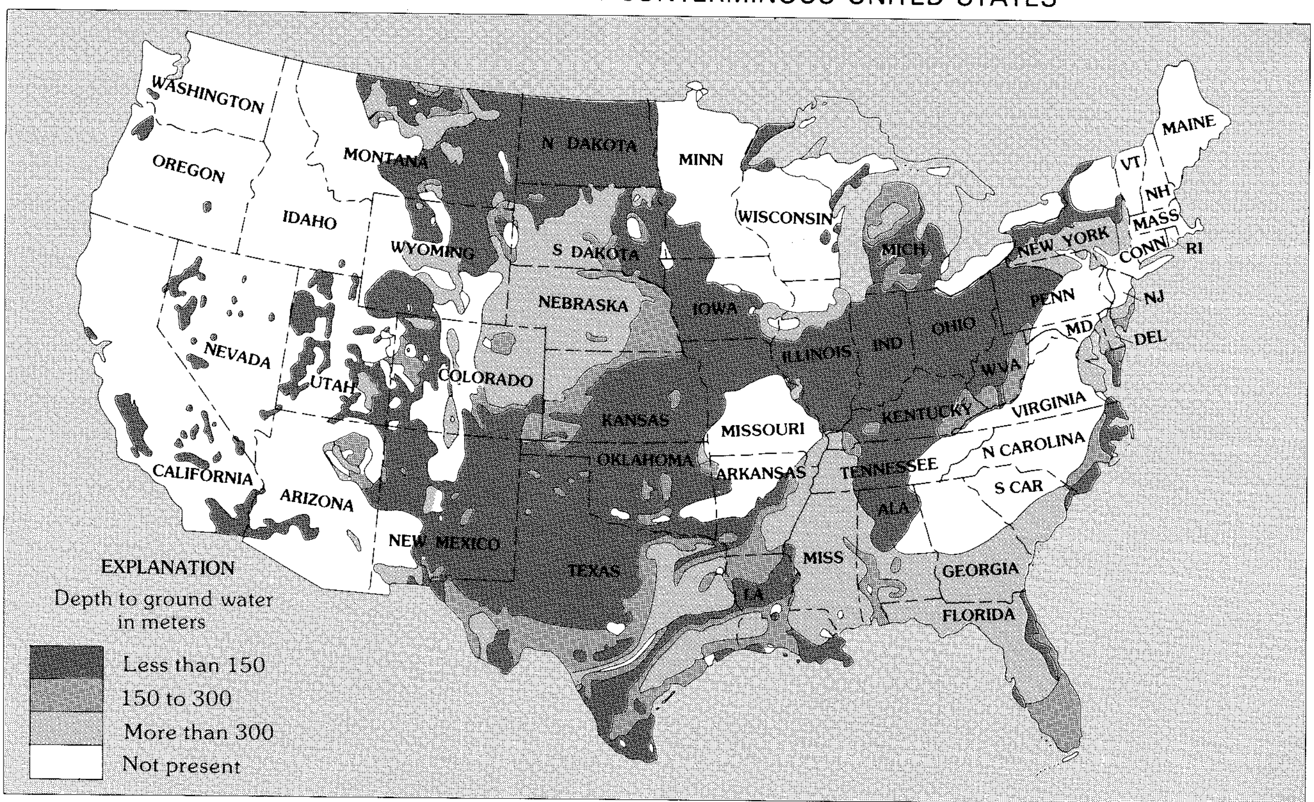
(1)

Two aspects of saltwater encroachment



(2)

DEPTH TO GROUND WATER CONTAINING MORE THAN 1000 mg/L OF TOTAL DISSOLVED SOLIDS IN THE CONTERMINOUS UNITED STATES



Todd, Groundwater Hydrology, 2nd Ed., 1980

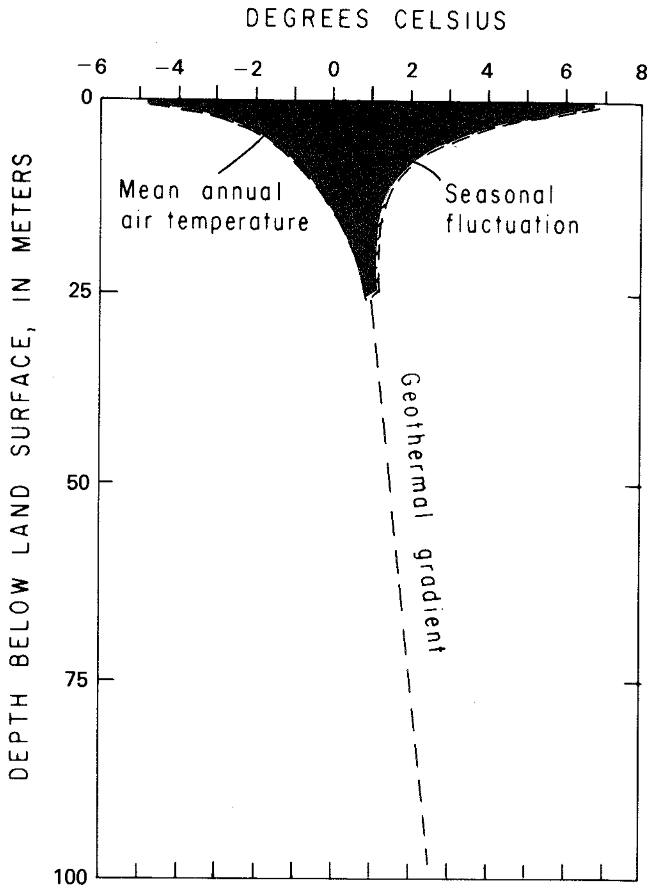
APPROXIMATE
0 200 400 600 MILES
0 200 400 600 KILOMETERS

(3)

Saltwater encroachment is a serious problem in some coastal areas. *Upconing of salty water* beneath pumping wells is a more imminent problem than *lateral encroachment* in most areas. One reason is that lateral encroachment must displace a volume of freshwater much larger than that displaced by upconing. Another reason is that approximately two-thirds of the United States is underlain by aquifers that yield water containing more than 1,000 mg/L of total dissolved solids (3). (See table 2 in "Quality of Ground Water.") In most places, these aquifers are overlain by other aquifers that contain freshwater and that serve as sources of water supply. However, where supply wells are drilled too deeply or are pumped at too large a rate, upconing of the mineralized (salty) water may occur.

In the design of supply wells in areas underlain by or adjacent to salty water, consideration must be given to the possibility of saltwater encroachment. This consideration may involve selection of shallow aquifers or small pumping rates to avoid upconing or involve moving wells to more inland locations to avoid lateral encroachment.

TEMPERATURE OF GROUND WATER



CHANGES IN GROUND-WATER TEMPERATURE WITH DEPTH

(1)

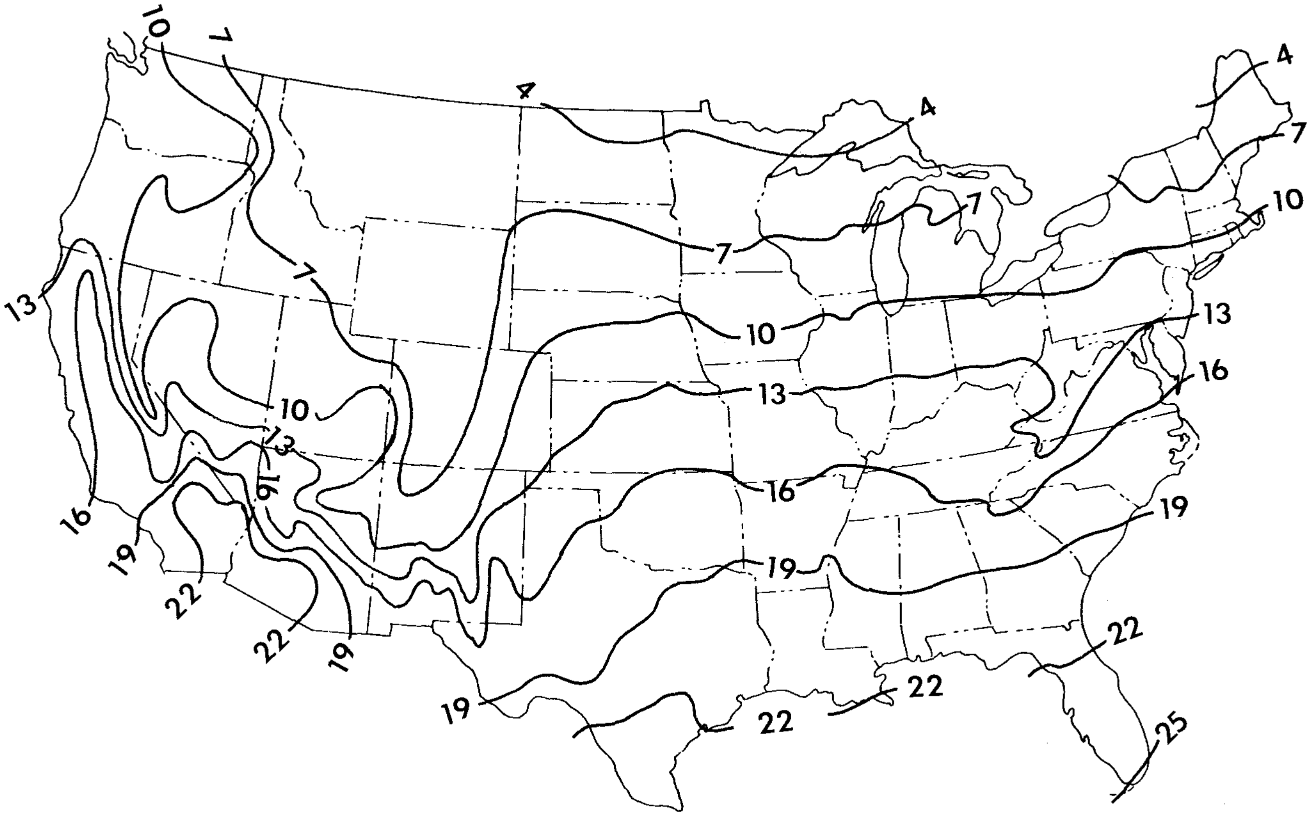
The temperature of ground water is one of its most useful characteristics. Ground water has been used for many years on Long Island, N.Y., and at other places as a heat-exchange medium for air-conditioning systems. As a result of recent increases in energy costs, ground water is also now becoming increasingly important as a source of heat for "heat pumps."

The temperature of ground water responds to seasonal variations in the heat received at the Earth's surface from the Sun and by movement of heat from the Earth's interior. The seasonal movement of heat into and out of the upper layers of the Earth's crust causes a seasonal fluctuation in ground-water temperatures to a depth of 10 to 25 m (1). The fluctuation is greatest near the surface, amounting to 5° to 10°C at depths of a few to several meters. In the zone affected by seasonal fluctuations, the mean annual ground-water temperature is 1° to 2°C higher than the mean annual air temperature (1). Consequently, a map showing the mean annual temperature of shallow ground water can be prepared on the basis of mean annual air temperature (sketch 2, based on a map showing mean annual air temperature prepared by the National Weather Service).

Movement of heat from the Earth's interior causes ground-water temperatures to increase with depth (1). This increase is referred to as the *geothermal gradient* and ranges from about 1.8°C per 100 m in areas underlain by thick sections of sedimentary rocks to about 3.6°C per 100 m in areas of recent volcanic activity. The effect of the geothermal gradient is not readily apparent in the zone affected by seasonal temperature fluctuations.

Movement of ground water causes a distortion in isotherms (lines depicting equal temperatures). This effect is most noticeable where ground-water withdrawal induces a movement of water from a stream into an aquifer. The distortion in ground-water temperature is most pronounced in the more permeable zones of the aquifer.

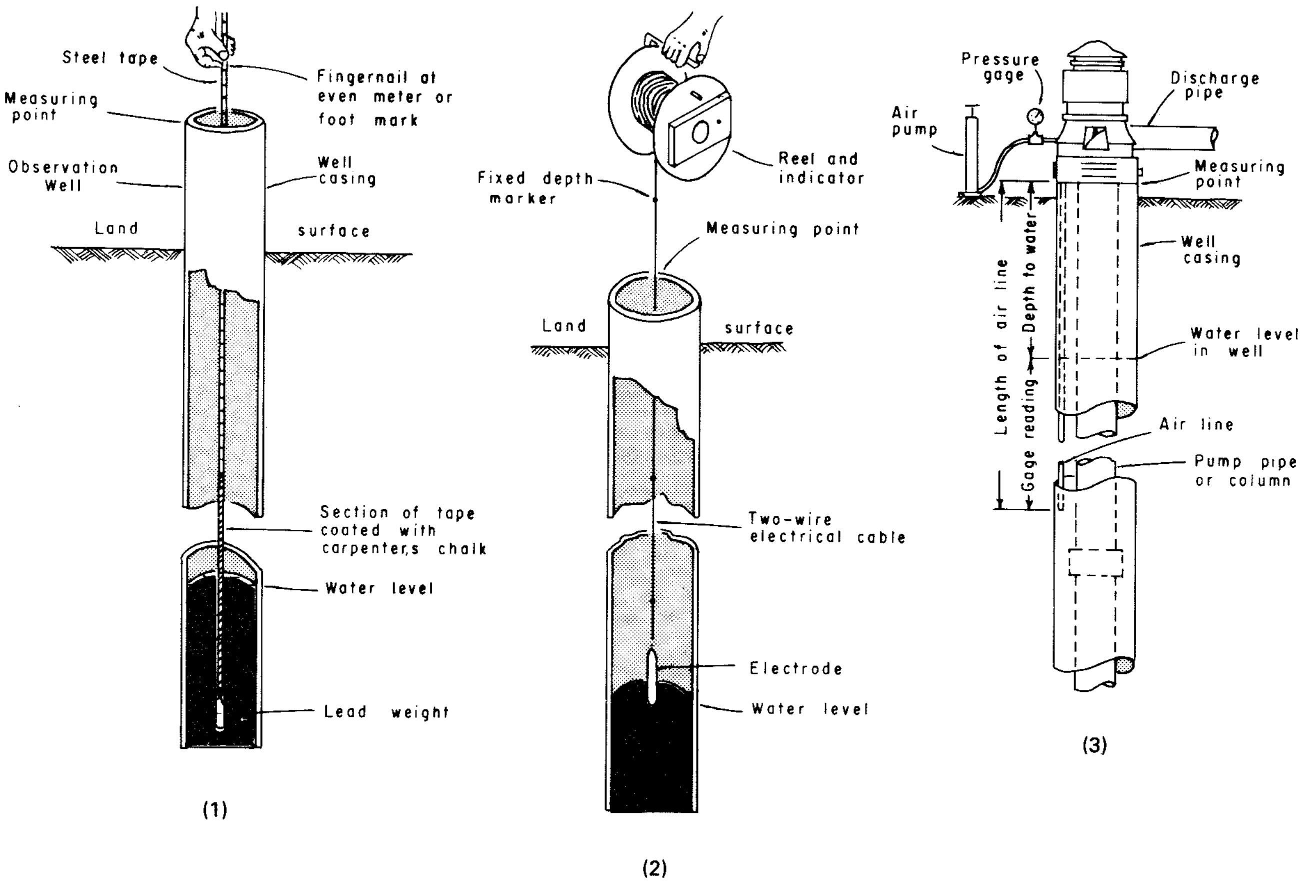
APPROXIMATE TEMPERATURE OF GROUND WATER, IN DEGREES CELSIUS, IN THE CONTERMINOUS UNITED STATES AT DEPTHS OF 10 TO 25 M



(2)

MEASUREMENTS OF WATER LEVELS AND PUMPING RATES

METHODS FOR MEASURING THE DEPTH TO WATER LEVEL IN WELLS



Each supply well, regardless of whether it is used for domestic, irrigation, industrial, or public-supply needs, should be provided with a means for measuring the position of the water level in the well. Public-supply and industrial wells should also be provided with a means for measuring the pumping rate. The use of water-level and pumping-rate measurements is discussed in "Supply-Well Problems—Decline in Yield."

The first step in measuring the position of the water level is to identify (and describe) a fixed point—that is, a *measuring point*—to which all measurements will be referred. This point is usually the top of the casing, well cap, or access port. The three most common methods used in measuring the depth to water in wells are wetted tape, electric tape, and air line.

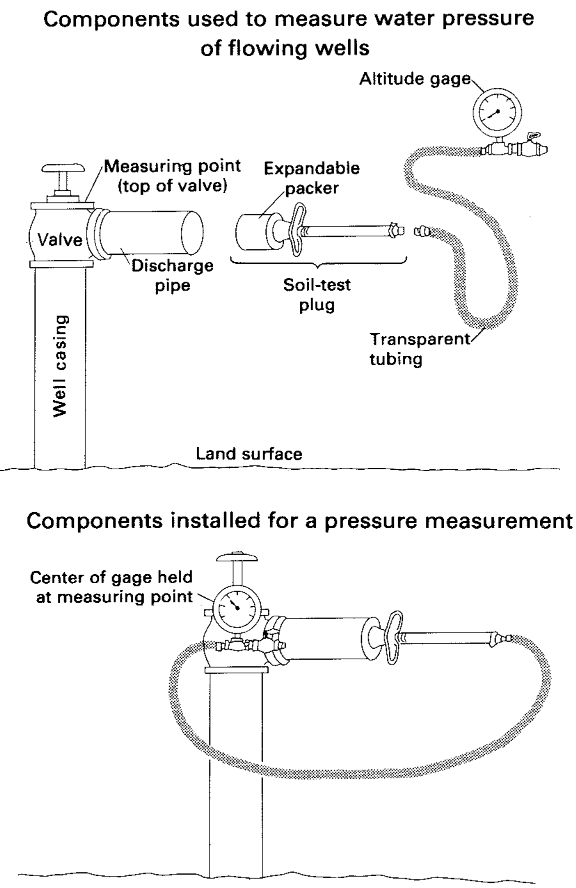
The *wetted-tape method* is probably the most common and most accurate of the three methods (1). This method utilizes a graduated steel tape with a weight attached to its end. The graduations on the lower meter (3 to 4 ft) of the tape are coated with blue carpenter's chalk, and the tape is lowered into the well until the lower part of the tape is submerged and an even meter (or foot) mark is at the measuring point. The tape is then quickly withdrawn, and the value held at the measuring point and the amount of tape that was submerged are entered on a record form. The amount of tape that was submerged is obvious from the change in color of the chalk coating. The depth to the water level below the measuring point is determined by subtracting the length of wet tape from the total length of tape that was lowered into the well.

The *electric-tape method* involves an ammeter connected across a pair of insulated wires whose exposed ends are separated by an air gap in an electrode and containing, in the circuit, a source of power such as flashlight batteries (2). When the electrode contacts the water surface, a current flows through the system circuit and is indicated by a deflection of the ammeter needle. The insulated wires are marked at 1-m (or 5 ft) intervals. The nail of the index finger is placed on the insulated wires at the measuring point when the ammeter indicates that the circuit is closed. A steel tape or carpenter's rule is used to measure the distance from the point indicated by the fingernail to the next highest meter (or 5 ft) mark. This distance is subtracted from the value of the mark to determine the depth to water. One difference between the wetted-tape method and the electric-tape method is that, in the wetted-tape method, the subtraction involves the length of the submerged tape, whereas, in the electric-tape method, the subtraction involves the distance between the measuring point and the next highest mark.

The *air-line method* is generally used only in wells on which pumps are installed. This method involves the installation of a small-diameter pipe or tube (the air line) from the top of the well to a point about 3 m (10 ft) below the lowest anticipated position of the water level during extended pumping periods (3). The water level in this pipe is the same as that in the well. To determine the depth to water, an air pump and a pressure gage are attached to the top of the air line. Air is pumped into the line to force the water out of the lower end. As the water level in the air line is depressed, the pressure indicated by the gage increases. When all the water has been forced out of the line, the pressure-gage reading stabilizes and indicates the length of the water column originally in the air line. If the pressure-gage reading is subtracted from the length of the air line below the measuring point, which was carefully determined when the air line was installed, the remainder is the depth to water below the measuring point.

The preceding discussion has covered the measurement of water levels in nonflowing wells—that is, in wells in which the water level is below the measuring point. In many coastal areas and valleys underlain by confined aquifers, water levels in wells will stand at some height above the land surface. These areas are referred to as *areas of artesian flow*, and the measurement of water levels in wells, where casings have not been extended above the static level, may pose problems. If the well is equipped with a valve and a threaded fitting, the height of the water level can be determined by attaching the appropriate pipe connection and a pressure gage or transparent plastic tube.

Measuring the water level of flowing wells not equipped with a valve or a threaded fitting requires the use of soil-test plugs or some other device to control the flow. The position of the static water level above the measuring point is determined either with a pressure gage or with a plastic tube (4).

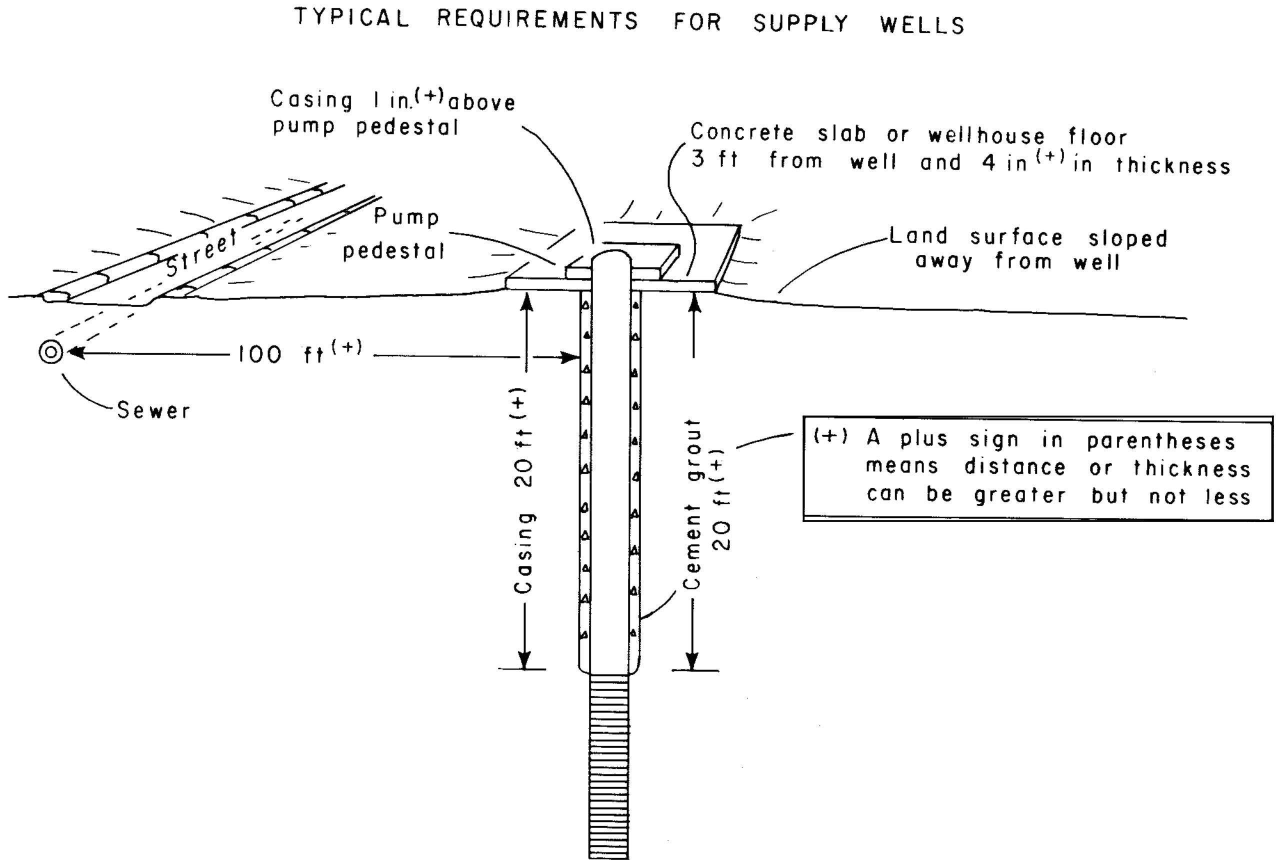


(4)

The *measurement of the pumping rates of supply wells* requires the installation of a flowmeter in the pump-discharge line. Either of two types of meters may be used, depending on the pumping rate. Up to a rate of about 1 m^3 min^{-1} (250 gal min^{-1}), an "active-element"-type meter may be used. These meters utilize either a propeller or a disk that is turned by the moving water. For larger pumping rates, meters that utilize a constriction in the discharge pipe are commonly used. These include venturi meters, flow nozzles, and orifices.

Flowmeters have dials that show either the total amount of water that has passed the meter or the rate at which the water is passing. With the first (the totalizing dial), the rate of discharge is determined by using a stopwatch to time the period for a certain volume of water to be pumped.

PROTECTION OF SUPPLY WELLS



Most, if not all, States have laws related to the location and construction of public-supply wells. These laws and the rules and regulations developed for their administration and enforcement are concerned, among other things, with protecting supply wells from pollution. Pollution of the environment results from man's activities, and, consequently, except where deep wells or mines are used for waste disposal, it primarily affects the land surface, the soil zone, and the upper part of the saturated (ground water) zone. Therefore, the protection of supply wells includes avoiding areas that are presently polluted and sealing the wells in such a way as to prevent pollution in the future.

Fortunately, most ground-water pollution at the present time affects only relatively small areas that can be readily avoided in the selection of well sites. Among the areas in which at least shallow ground-water pollution should be expected are:

1. **Industrial districts** that include chemical, metalworking, petroleum-refining, and other industries that involve fluids other than cooling water.
2. **Residential areas** in which domestic wastes are disposed of through septic tanks and cesspools.
3. **Animal feedlots** and other areas in which large numbers of animals are kept in close confinement.
4. **Liquid and solid waste disposal sites,** including sanitary landfills, "evaporation ponds," sewage lagoons, and sites used for the disposal of sewage-plant effluent and solid wastes.
5. **Chemical stockpiles,** including those for salt used to deice streets and highways and for other chemical substances soluble in water.

In the selection of a well site, areas that should be avoided include not only those listed but also the zones surrounding them that may be polluted by movement of wastes in response to both the natural hydraulic gradient and the artificial gradient that will be developed by the supply well.

Rules and regulations intended to prevent future pollution include provision of "exclusion" zones around supply wells, requirements for casing and for sealing of the annular space, and sealing of the upper end of the wells.

Many State regulations require that supply wells be located at least 100 ft (30 m) from any sources or potential sources of pollution. In the case of public-supply wells, the well owner must either own or control the land within 100 ft (30 m) of the well. In some States, a public-supply well may be located as close as 50 ft (15 m) to a sewer if the joints in the sewerline meet water-main standards.

Some State regulations require that all supply wells be cased to a depth of at least 20 ft (6 m) and that the annular space between the land surface and a depth of 20 ft (6 m) be completely filled with cement grout. The casing of supply wells drawing water from fractured bedrock must be seated and sealed into the top of the rock.

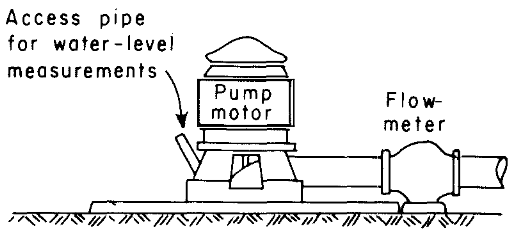
Most regulations require that the casing of all supply wells terminate above land surface and that the land surface at the site be graded or sloped so that surface water is diverted away from the well. Many States also require that public-supply wells have a continuous-bond concrete slab or concrete wellhouse floor at least 4 in. (10 cm) thick and extending at least 3 ft (1 m) horizontally around the outside of the well casing. The top of the well casing must project not less than 6 in. (15 cm) above the concrete slab or wellhouse floor. The top of the well casing must also project at least 1 in. (2.5 cm) above the pump pedestal. The top of the well casing must be sealed watertight except for a vent pipe or vent tube having a downward-diverted screened opening.

The regulations cited above provide, at best, only minimal protection for supply wells. There are numerous situations in which both the size of the exclusion zone and the depth of casing are inadequate. Relative to the radius of the exclusion zone, there are no arbitrary limits, except the physical boundaries of an aquifer, past which ground water cannot move. Relative to the minimum required casing, there are no vertical limits, except for the impermeable base of the ground-water system, past which polluted water cannot move.

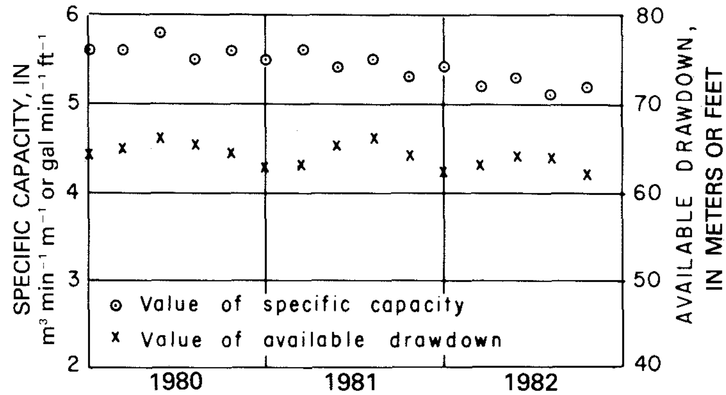
On the other hand, there are geologic and hydrologic situations in which these regulations may be unnecessarily restrictive. An example is pollution in an unconfined aquifer down the hydraulic gradient from a supply well drawing from a deep confined aquifer overlain by a nonleaky confining bed.

Because of these factors, it is essential that officials involved in regulating the location and construction of supply wells be adequately trained in the fields of ground-water geology and hydrology so that they can protect the public health on the basis of scientific knowledge and technical judgment rather than that of blind application of arbitrary regulations.

SUPPLY-WELL PROBLEMS—DECLINE IN YIELD



(1)



(2)

The yield of any water-supply well depends on three elements: the aquifer, the well, and the pump. A decline in yield is due to a change in one of these elements, and correction of the problem depends on identification of the element that is involved. This identification in many cases can be made only if data are available on the depth to the water level in the well and the pumping rate. Inability to identify reasons for a decline in yield frequently results in discontinuing the use of ground water and developing more expensive supplies from surface-water sources.

The *depth to the water level* in a well equipped with a pump may be determined by using a steel tape, an electric tape, or an air line and pressure gage. The *pumping rate of a supply well* can be determined by any one of several different types of metering devices (1). (See "Measurements of Water Levels and Pumping Rates.")

The yield of a well depends on the drawdown and on the specific capacity. The *specific capacity* is the yield per unit of drawdown, and, in nearly all pumping wells, it varies with the pumping rate. Therefore, a discussion of decline in yield is meaningful only in terms of the maximum yield. The *maximum yield* of a well is controlled by the available drawdown and the specific capacity when the drawdown in the well equals the available drawdown. (See "Well-Acceptance Tests and Well Efficiency.")

The *available drawdown* is determined at the time of construction of a supply well and consists of the difference between the static (nonpumping) water level and the lowest practical pumping level. The *lowest practical pumping level* depends on the type of well. In screened wells, it is at the top of the uppermost screen. In open-hole fractured-rock wells, it is at the position of the lowest water-bearing fracture or at the lowest level at which the pump intake can be placed.

The specific capacity and the "yield" of supply wells are determined at the time of well construction. If the pumping level during the well-acceptance test is relatively close (within a few meters) to the lowest practical level, the specific capacity determined during the test can be used to accurately estimate the maximum yield. However, it is important to note that apparent declines in yield after wells are placed in production reflect, in many cases, overestimation of the yields at the time of construction. Actual declines in yield after wells are placed in operation result from deterioration of pumps, declines in the static water level or the specific capacity, or combinations of all three.

The yield of a well field is the sum of the yields of the individual wells. Successful operation, therefore, requires periodic measurements of both the specific capacity and the available drawdown for each well. Changes in these values are used to predict the yield of the field at different times in the future and, when they are used in conjunction with predictions of needs, to plan the rehabilitation of existing wells or the construction of new wells.

Measurements of specific capacity and available drawdown are neither difficult nor time consuming. The determination of both requires only the three measurements listed below:

1. *Static (nonpumping) water level* (w. l.), measured weekly near the end of the longest nonpumping period, which, in most systems with large industrial uses, is near the end of the weekend.
2. *Maximum pumping water level*, measured weekly near the end of the longest period of continuous use, which, in most water systems, is near the end of the workweek.
3. *Pumping rate*, measured at the same time as the maximum pumping water level.

These three items of data are analyzed as follows to determine the maximum yield of the well.

specific capacity

$$= \frac{\text{pumping rate (m}^3\text{ min}^{-1}\text{ or gal min}^{-1})}{\text{static w. l. (m or ft)} - \text{pumping w. l. (m or ft)}}$$

$$= \frac{\text{m}^3}{\text{min m}} \text{ or } \frac{\text{gal}}{\text{min ft}}$$

available drawdown (m or ft)
= (static water level, in m or ft) − (lowest practical water level, in m or ft)

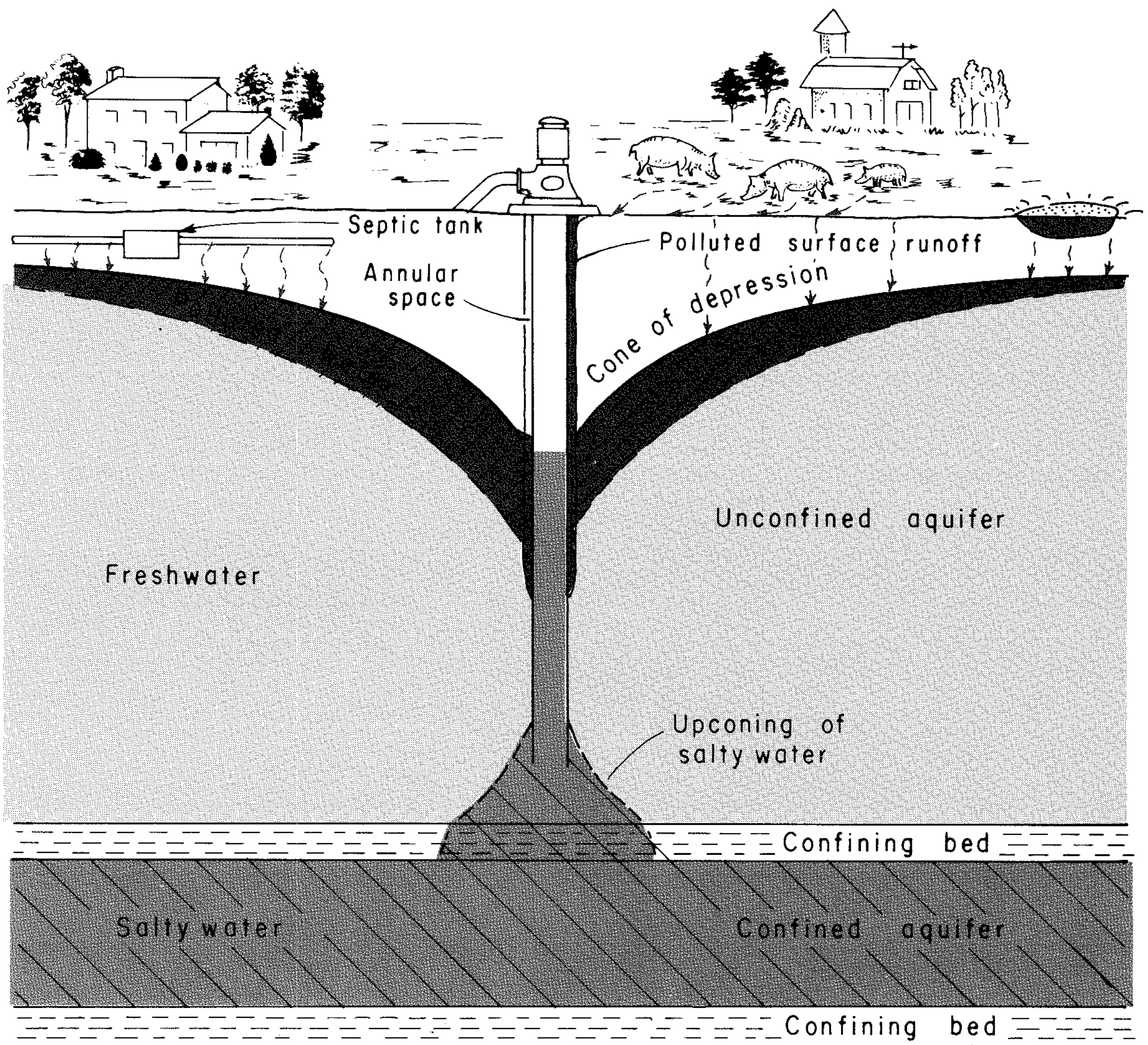
maximum yield = (specific capacity) × (available drawdown)

Determinations of specific capacity and available drawdown should be carefully preserved as a part of the permanent file on each well. (See "Well Records and Files.") They should be analyzed at least quarterly to determine if changes in either are occurring. This analysis can be done most conveniently if the values are plotted on graph paper versus the time of the determination (2). Changes in available drawdown and (or) specific capacity and suggested causes and corrective action are listed in the accompanying table.

ANALYSIS OF DECLINES IN WELL YIELD

Identifying criteria	Cause	Corrective action
Decline in available drawdown, no change in specific capacity.	The aquifer, due to a decline in ground-water level resulting from depletion of storage caused by decline in recharge or excessive withdrawals.	Increase spacing of new supply wells. Institute measures for artificial recharge.
No change in available drawdown, decline in specific capacity.	The well, due to increase in well loss resulting from blockage of screen by rock particles or by deposition of carbonate or iron compounds; or reduction in length of the open hole by movement of sediment into the well.	Redevelop the well through the use of a surge block or other means. Use acid to dissolve encrustations.
No change in available drawdown, no change in specific capacity.	The pump, due to wear of impellers and other moving parts or loss of power from the motor.	Recondition or replace motor, or pull pump and replace worn or damaged parts.

SUPPLY-WELL PROBLEMS—CHANGES IN WATER QUALITY



The problems most frequently encountered in the operation of supply wells relate either to declines in yield or to deterioration in the quality of the water. Declines in yield are discussed in "Supply-Well Problems—Decline in Yield."

Deterioration in water quality may result either from changes in the quality of water in the aquifer or changes in the well. These changes may affect the biological quality, the chemical quality, or the physical quality. Deterioration in biological and chemical quality generally results from conditions in the aquifer, whereas changes in physical quality result from changes in the well.

Both the biological and the chemical quality of water from new public-supply wells must be analyzed before the wells are placed in use to determine if the water meets water-supply standards and, if it does not, what treatment is required. Drinking-water regulations of the U.S. Environmental Protection Agency also require that analyses of biological quality be made monthly and that analyses of inorganic quality be made at least every 3 years for all community systems supplied entirely by ground water. It is good practice to periodically determine the biological and chemical quality of water from all wells, especially those that supply domestic needs, in order to determine if changes in quality are occurring.

Deterioration in *biological quality* refers to the appearance in the water of bacteria and (or) viruses associated with human or animal wastes. Such deterioration is referred to under the general term *pollution* and indicates, in nearly all cases, a connection between the land surface or a near-surface zone and the open section of the well. The connection most frequently exists in the annular space between the casing and the aquifer. To avoid pollution of wells, many well-construction regulations require that the annular space be completely filled with cement grout from the land surface to a depth of at least 20 ft (6 m).

Deterioration in chemical quality refers to the arrival at a supply well of water containing dissolved chemicals in an undesirably large concentration. Withdrawals of water from a well cause water to converge on the well from different directions. If this convergence involves water containing a large concentration of any substance, the concentration of that substance will, after some period of time, begin to increase. The most commonly observed increases in concentration involve NaCl (sodium chloride or common salt) and NO_3 (nitrate), but, if the well is near a sanitary landfill or other waste-disposal site, the increase may involve almost any substance commonly used by man.

Nitrate is an important constituent in fertilizers and is present in relatively large concentrations in human and animal wastes. Therefore, nitrate concentrations in excess of a few milligrams per liter almost invariably indicate that water is arriving at the well from shallow aquifers that are polluted by septic tanks or animal feedlots or that are contaminated by excess nitrates used in farming operations.

Sodium chloride is the principal constituent of seawater and is also present in significant concentrations in human and animal wastes and in some industrial wastes. An increase in the chloride content in well water most commonly indicates upward movement of water from an underlying zone of salty water. Other increases are due to pollution by sources at or near the land surface, such as deicing operations on streets and highways in the northern part of the country.

Although increases in chloride and nitrate content are probably the most common changes in chemical quality that occur in ground water, changes may involve almost any substance soluble in water. Thus, it is important to be aware of the accidental or intentional release of potential pollutants within the area of influence of all supply wells. Substances that are of particular concern in this regard include herbicides, pesticides and other complex organics, petroleum products, and those substances that contain trace concentrations of metals. In planning a sampling program, for these substances or any others, it is important to consider the slow rate at which most ground water moves.

Deterioration in physical quality involves changes in appearance, taste, and temperature. Most commonly, a change in appearance or color involves either the gradual or the sudden appearance of rock particles in the water. These particles can range in size from clay, which gives the water a turbid or "bluish" appearance, to sand. The size of the particles is indicated by the rate at which the particles settle. If the particles settle exceedingly slowly, or not at all, they are clay size. If they settle immediately, they are sand size.

The gradual appearance of particles generally indicates that the finer grained material was not adequately removed from the zone adjacent to the well during well development. (See "Well-Construction Methods.") During use of the well, these particles slowly migrate to and into the well. The sudden appearance of particles—that is, when the concentration of particles is large (very obvious) from the beginning—generally indicates the failure (collapse) of the screen or a rupture of the well casing.

Changes in the quality of water produced by a well, likely causes of the change, and suggested corrective action are listed in the accompanying table.

ANALYSIS OF CHANGES IN WATER QUALITY

Change in quality	Cause of the change	Corrective action
Biological ---------	Movement of polluted water from the surface or near-surface layers through the annular space.	Seal annular space with cement grout or other impermeable material and mound dirt around the well to deflect surface runoff.
Chemical ---------	Movement of polluted water into the well from the land surface or from shallow aquifers.	Seal the annular space. If sealing does not eliminate pollution, extend the casing to a deeper level (by telescoping and grouting a smaller diameter casing inside the original casing).
	Upward movement of water from zones of salty water.	Reduce the pumping rate and (or) seal the lower part of the well.
Physical ----------	Migration of rock particles into the well through the screen or from water-bearing fractures penetrated by open-hole wells.	Remove pump and redevelop the well
	Collapse of the well screen or rupture of the well casing.	Remove screen, if possible, and install new screen. Install smaller diameter casing inside the original casing.

WELL RECORDS AND FILES

The collection and preservation of records on the construction, operation, maintenance, and abandonment of supply wells are an essential but largely neglected activity. This responsibility rests largely on the well owner or operator. The consequence of this neglect is that it is not possible to identify and to economically correct problems of declining yield or deterioration in water quality, and the design of new wells cannot incorporate past operational experience.

A file should be established on each supply well at the time when plans for its construction are initiated. From the initial planning to the final abandonment of the well, the following records should be generated and carefully preserved in this file:

1. **Initial design,** including drawings or written specifications on diameter, proposed total depth, position of screens or open hole, method of construction, and materials to be used in construction. (See "Water-Well Design.")
2. **Construction record,** including the method of construction and the driller's log and a geophysical log of the materials penetrated during construction, the diameter of casings and screens, the slot size and metallic composition of screens, the depths of casing and screens, the total depth of the well, and the weight of the casing. (See "Well-Construction Methods" and "Well Logs.") Records and logs should also be retained for all test wells, including those that were not successful because of small yields.
3. **Well-acceptance test,** including a copy of the water-level measurements made before, during, and after the drawdown (pumping) test, a record of the pumping rate or rates, copies of any graphs of the data, and a copy of the hydrologist's report on the interpretation of the test results. (See "Well-Acceptance Tests and Well Efficiency.")
4. **Pump and installation data,** including the type of pump, the horsepower of the motor, the depth to the pump intake, a copy of the pump manufacturer's performance and efficiency data, and data on the length of the air line or a description of facilities provided for water-level measurements, including a description of the measuring point. (See "Measurements of Water Levels and Pumping Rates.")
5. **Operating record,** including data on the type of meter used to measure the flow rate, weekly readings of the flowmeter dial, weekly measurements of the static and pumping water levels, and periodic analyses of water quality. (See "Supply-Well Problems—Decline in Yield.")
6. **Record of well maintenance,** including the dates and the activities instituted to increase the yield or to improve the water quality and data showing the results achieved. (See "Supply-Well Problems—Decline in Yield" and "Supply-Well Problems—Changes in Water Quality.")
7. **Record of well abandonment,** including the date that use of the well was discontinued and a description of the methods and materials used to seal or plug the well.

The type of forms used for the records described above is not of critical importance. It is more important that the records be collected, regardless of the type of form that is used. It is important, however, that the date and the watch time be noted with each measurement of pumping rate and depth to water and on each water sample collected for water-quality analyses.

REFERENCES

A large number of publications on ground-water hydrology were consulted in the preparation of this report. A citation is shown in the text only where a publication was used as a specific source of tabular data.

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NUMBERS, EQUATIONS, AND CONVERSIONS

The preceding discussions of basic ground-water hydrology involve the use of equations and physical units with which some readers may not be familiar. This discussion of numbers, equations, and conversion of units from one system of measurement to another is included for the benefit of those readers and for others who need to refresh their memories.

Expressing Large Numbers

$1{,}000 = 10 \times 10 \times 10 = 1 \times 10^3$

$1{,}000{,}000 = 10 \times 10 \times 10 \times 10 \times 10 \times 10 = 1 \times 10^6$

The numbers 3 and 6 are called exponents and indicate the number of times that 10 must be multiplied by itself to obtain the initial number.

Expressing Small Numbers

$$0.001 = \frac{1}{1{,}000} = \frac{1}{1 \times 10^3} = 1 \times 10^{-3}$$

$$0.000001 = \frac{1}{1{,}000{,}000} = \frac{1}{1 \times 10^6} = 1 \times 10^{-6}$$

Exponents in the denominator acquire a negative sign when they are moved to the numerator.

Simplifying Equations

Symbols in equations have numerical values and, in most cases, units of measurement, such as meters and feet, in which the values are expressed. For example, Darcy's law, one of the equations used in basic ground-water hydrology, is

$$Q = KA\left(\frac{dh}{dl}\right)$$

In metric units, hydraulic conductivity (K) is in meters per day, area (A) is in square meters, and hydraulic gradient (dh/dl) is in meters per meter. Substituting these units in Darcy's law, we obtain

$$Q = \frac{\text{meters}}{\text{day}} \times \text{meters}^2 \times \frac{\text{meters}}{\text{meters}} = \frac{\text{meters}^4}{\text{meters day}} = \text{m}^{4-1}\ \text{d}^{-1} = \text{m}^3\ \text{d}^{-1}$$

Similarly, in inch-pound units, K is in feet per day, A is in square feet, and dh/dl is in feet per feet. Substituting these units in Darcy's law, we obtain

$$Q = \frac{\text{feet}}{\text{day}} \times \text{feet}^2 \times \frac{\text{feet}}{\text{feet}} = \frac{\text{feet}^4}{\text{feet day}} = \text{ft}^{4-1}\ \text{d}^{-1} = \text{ft}^3\ \text{d}^{-1}$$

The characteristics of exponents are the same, whether they are used with numbers or with units of measurement. Exponents assigned to units of measurement are understood to apply, of course, to the value that the unit of measurement has in a specific problem.

Conversion of Units

Units of measurements used in ground-water literature are gradually changing from the inch-pound units of gallons, feet, and pounds to the International System of units of meters and kilograms (metric units). It is, therefore, increasingly important that those who use this literature become proficient in converting units of measurement from one system to another. Most conversions involve the fundamental principle that the numerator and denominator of a fraction can be multiplied by the same number (in essence, multiplying the fraction by 1) without changing the value of the fraction. For example, if both the numerator and the denominator of the fraction 1/4 are multiplied by 2, the value of the fraction is not changed. Thus,

$$\frac{1}{4}\times\frac{2}{2}=\frac{2}{8}=\frac{1}{4} \text{ or } \frac{1}{4}\times\frac{2}{2}=\frac{1}{4}\times 1=\frac{1}{4}$$

Similarly, to convert gallons per minute to other units of measurement, such as cubic feet per day, we must first identify fractions that contain both the units of time (minutes and days) and the units of volume (gallons and cubic feet) and that, when they are used as multipliers, do not change the numerical value. Relative to time, there are 1,440 minutes in a day. Therefore, if any number is multiplied by 1,440 min/d, the result will be in different units, but its numerical value will be unchanged. Relative to volume, there are 7.48 gallons in a cubic foot. Therefore, to convert gallons per minute to cubic feet per day, we multiply by these "unit" fractions, cancel the units of measurement that appear in both the numerator and the denominator, and gather together the units that remain. In other words, to convert gallons per minute to cubic feet per day, we have

$$\frac{\text{gallons}}{\text{minute}}=\frac{\text{gallons}}{\text{minute}}\times\frac{1{,}440\text{ min}}{\text{d}}\times\frac{\text{cubic feet}}{7.48\text{ gal}}$$

and, canceling gallons and minutes in the numerators and denominators, we obtain

$$\frac{\text{gallons}}{\text{minute}}=\frac{1{,}440\text{ ft}^3}{7.48\text{ d}}=192.5\text{ ft}^3\text{ d}^{-1}$$

which tells us that 1 gal min^{-1} equals 192.5 $\text{ft}^3\text{ d}^{-1}$.

We follow the same procedure in converting from inch-pound units to metric units. For example, to convert square feet per day to square meters per day, we proceed as follows:

$$\frac{\text{ft}^2}{\text{d}}=\frac{\text{ft}^2}{\text{d}}\times\frac{\text{m}^2}{10.76\text{ ft}^2}=\frac{\text{m}^2}{10.76\text{ d}}=0.0929\text{ m}^2\text{ d}^{-1}=9.29\times10^{-2}\text{ m}^2\text{ d}^{-1}$$

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